United States
Department of
Agriculture

Forest Service

FORESTRY DECISIONS

Stephen G. Boyce

Southeastern Forest
Experiment Station

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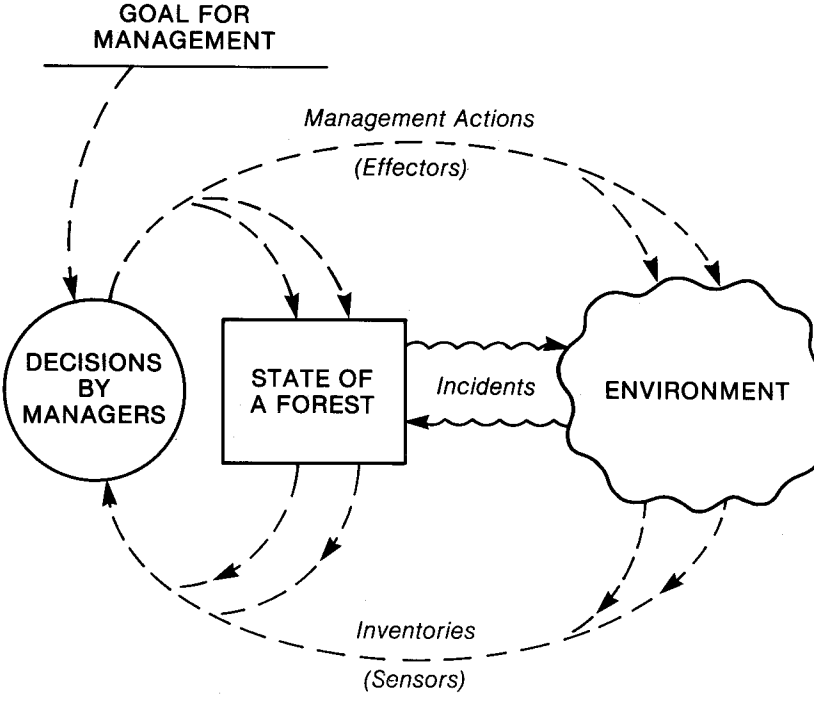

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Forestry Decisions

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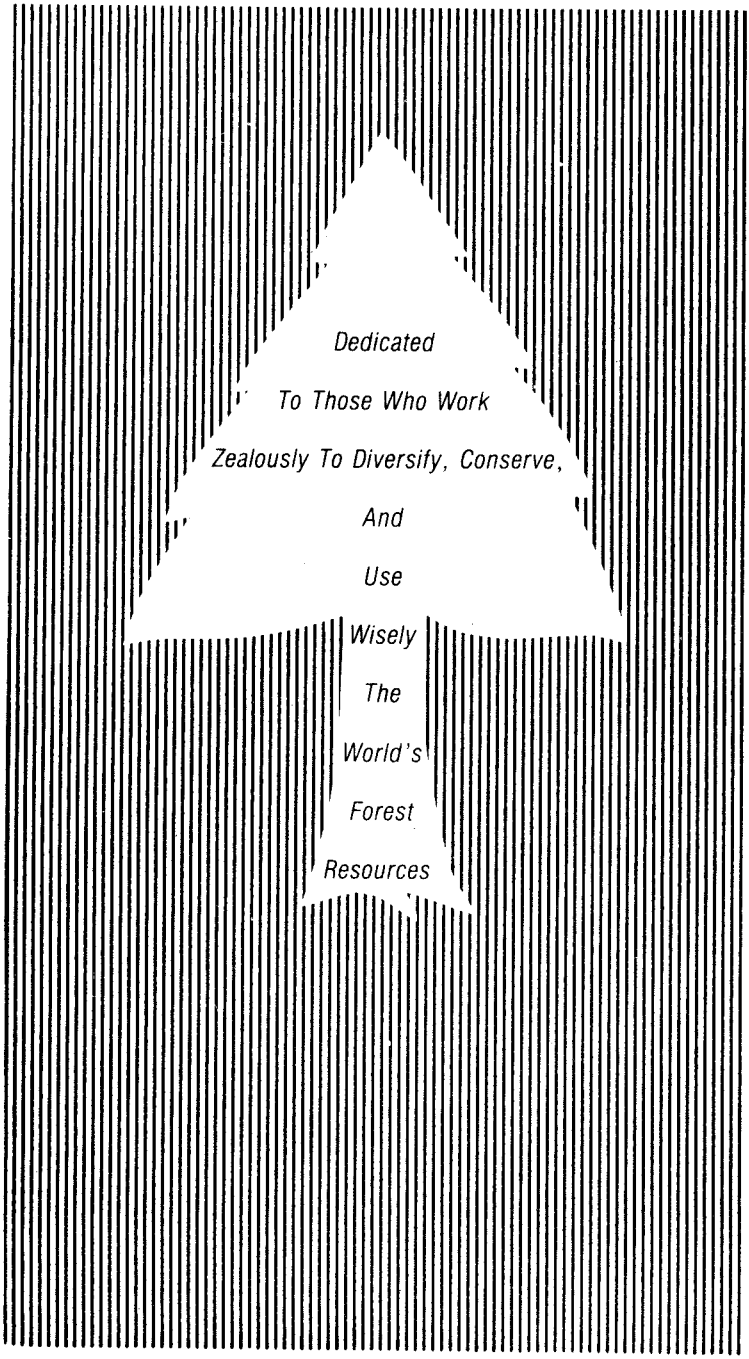
Dedicated
To Those Who Work
Zealously To Diversify, Conserve,
And
Use
Wisely
The
World's
Forest
Resources

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Preface

Conservation rather than liquidation is the theme of forestry. Scheduled removals of game and timber are for the purpose of having food, shelter, heat, and other benefits in perpetuity. From this theme came the rallying phrases for forestry: "sustained yield," "the greatest good for the greatest number," "multiple benefits," "even flow," "regulated forests," and "living in harmony with nature." The ideals expressed by these phrases are simple and appealing; implementation is very difficult.

This book describes a new direction for implementing the theme of forestry. The scheduling of harvest and culture found so useful is preserved. What is new is the question that leads to decisions and to control of the forests. Instead of asking, "How much game, timber, this, and that do we want to produce?," we ask, "If we do this, what will we have?" Decisions are answers to the questions: How will this or that schedule of culture change the forest over time? What monetary returns will we have? What will be the stream of benefits? What will be the potential productivity of the forest?

This simple change in questioning the choice of decisions and the use of controls changes the way we view a forest. Rather than viewing a forest as a manufacturing plant putting together timber, game, and other benefits at the will of managers, a forest is viewed as a biological system that self-organizes in response to culture. Control becomes a process of using culture to direct the self-organizing forces to transform the forest from the present state through a stream of desired future states. Each state of forest organization provides some combination of materials for harvest and some physical structure for non-harvestable benefits.

This new direction is the basis for providing game and nongame animals; trees for timber; shrubs and herbaceous plants; and, possibly most important, conservation of a wide variety of germ plasm for the livelihood of man. This new direction depends on the concept that behavior of complex ecosystems, such as forests, is principally caused by structure--how the component parts are connected. These connections direct the flows of information, energy, and materials through feedback loops to integrate the behavior of the systems' elements. The result is a decision and control procedure that crosses forestry disciplines without conflict.

Optimal strategy is derived by subjective decisions determined by insights, value judgments, experience, and acumen of interested parties. The responsibilities of administrators are not usurped in mathematical expressions; mental models and scientifically derived relationships are communicated explicitly; people make the decisions.

Many people contributed to my ideas and concepts, which evolved over five decades of observing, posing questions, and searching for answers. The thoughts, perceptions, and insights of Professor Bertram W. Wells, North Carolina State University, are worthy of special note. It was Professor Wells who suggested in 1951 that the dynamics of coastal vegetation under the influence of salt spray may be interpreted within the framework of cybernetics (Wiener 1961). From these discussions the four bionomic theories were drafted in 1951, and the falsification hypotheses for the theories guided my studies of plant responses to salt spray (Boyce 1954) and many later studies. The theories were formally published 26 years later and are the foundation for this book (Boyce 1977, 1978b).

My sincere appreciation is extended to my students and to many people who posed questions, challenges, and suggestions; tolerated my questions; and helped me to structure the information I present in this book.

Stephen G. Boyce
August 1985

Acknowledgment

The information included here was published as technical and professional papers by the United States Department of Agriculture Forest Service. This book began as a set of lectures when I held an appointment at the School of Forestry and Environmental Studies, Yale University, from 1979 to 1981. The course is now taught at the School of Forestry and Environmental Studies, Duke University.

Chapter 1

Introduction

The Human Use of Forests

This book tells how to use forests. Its focus is on providing multiple benefits within the biological limits for sustaining productivity of the forest and land. The chore is to use cultural practices, called silviculture, to direct the behavior of biological systems and bring about a desired state of organization of the forest. This process is the silvicultural application of ecosystem dynamics.

The purpose of the process described here is to help parties identify alternative combinations of uses and help them choose a combination of uses acceptable to their best interest. The method is to display the dynamics of selected combinations of benefits, impacts, and costs in simple charts and tables and to allow people to use judgment, insight, and experience to make subjective decisions. Decisions are for a decade or less; control is through silviculture. Cybernetic techniques keep plans dynamic and congruent with the real forest and with the perceptions of interested parties. The simulations incorporate the results of inventories, research, and monitorings; limit the displays to biologically possible combinations of benefits; and relate each combination of benefits to the silvicultural cost.

The question asked is: To what dynamic state of organization do the interested parties want to bring this forest? The answer, derived from each party's perceptions of best interest, is a state of forest organization toward which all silviculture is directed. Benefits, costs, and impacts are related, independently of each other, to

orderly changes in states of forest organization. Cultural actions are harmonized to modify the natural ecosystem dynamics and thus direct the forest toward the chosen state.

Near the end of each planning period, the entire decision and control process is repeated. New information is added to the simulations; different perceptions and possibly different interested parties are used in the subjective choice of an adjusted goal. In this manner, a new structure for managing the forest is derived.

Forests are viewed as nonequilibrium, dynamic systems constantly transforming from one state of organization to another (Boyce 1978b). These aimless transformations, modified by silviculture and use, bring about the communities of plants and animals we call stands. They are driven by natural sources of energy and material and have provided food, shelter, clothing, and other benefits to man for thousands of years (fig. 1). The benefits, produced without silviculture, are essentially free except for the costs involved in owning, harvesting, and protecting the forests. It is likely that most of the benefits from the world's forests result from little or no investment in silviculture.

Many forests are converted to homes and highways--uses that are considered to be more valuable than the benefits derived from natural ecosystems. I have not included conversion of forests to nonforest uses in this book. My primary concern is the purposeful and systematic modification of forests without destruction of the natural ecosystem dynamics that have been going on for millions of years.

Silviculture is viewed as the culture of forests for any and all benefits, singly and in different combinations. Silviculture is used to direct ecosystem dynamics for increased amounts

and improved quality of benefits (fig. 2). It requires decisions to invest management resources such as labor, capital, and knowledge. Although these investments are expected to improve human benefits, the most important constraint on silviculture is biology. It is apparent that decision and control techniques are required to provide benefits within the biological limits for sustaining long-term productivity of the forest and land.

This book describes a cybernetic decision and control system. The system is guided toward a goal by feedback processes, and it is based on a simulation of the managed forest. The timber harvest is regulated to guide the forest toward a steady-state distribution of habitats yielding a constant annual flow of harvested timber and other benefits. The cybernetic method is used to periodically adjust the goal, within the biological limits, in relation to changes in social, economic, and political forces.

Benefits are defined by people in relation to personal interest. The definition includes the satisfaction of viewing a forested scene from a roadside overlook; making a livelihood by harvesting, processing, and marketing timber; using wooden furniture and a newspaper; and enjoying a paneled wall and a pleasant hike. Perceptions of benefits change faster than forests can transform from state to state. In other words, technology for processing tangible benefits changes faster than forest managers can genetically and physiologically modify the physical properties of biomass. Economic cycles and social attitudes change faster than forest managers can transform forest states. Thus, the use of silviculture to match combinations of benefits with perceptions of personal interests requires dynamic plans that are designed with cybernetic principles to integrate personal perceptions of interested parties with ecosystem dynamics.

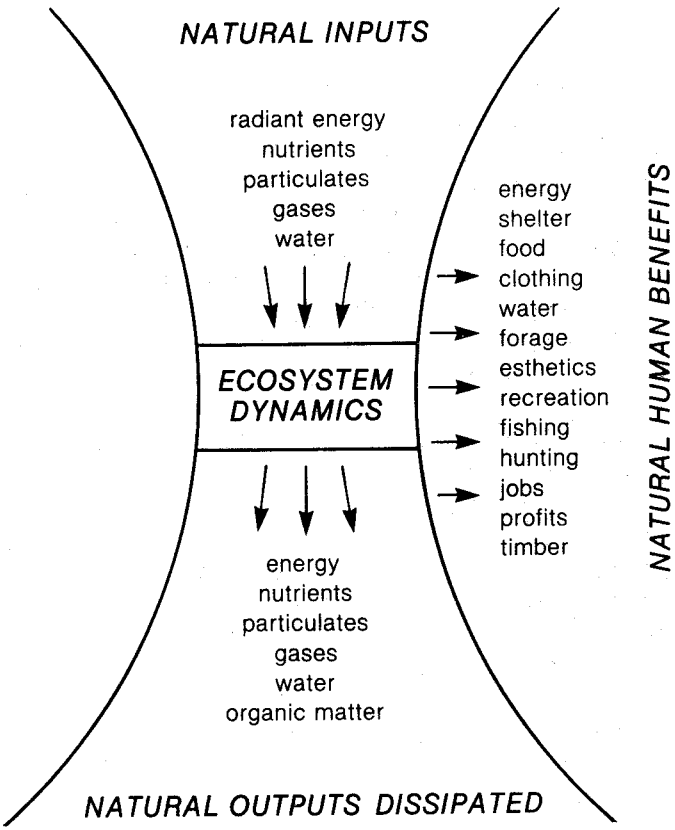


Figure 1.--Human benefits derived from forest ecosystems without silviculture.

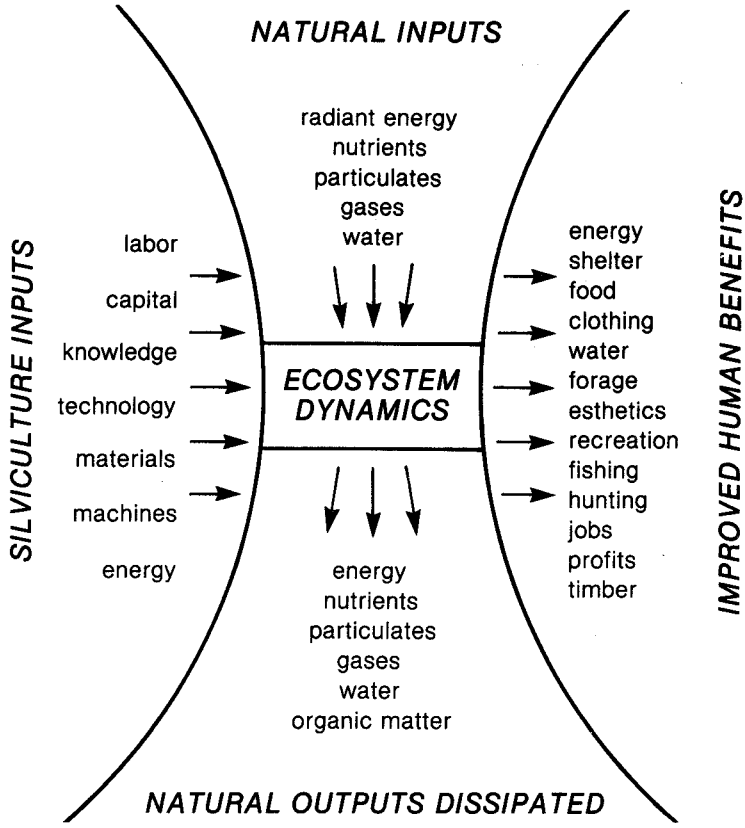


Figure 2.--The use of silviculture to direct ecosystem dynamics for more and better benefits.

Ecosystem dynamics includes transforming communities of organisms from one state of organization to another and the behavior, evolution, and extinction of large numbers of plants and animals. Although these transformations are aimless, observations of repeated changes from state to state provide information for projecting transformations for short time periods. For example, we may observe that most stands whose trees now average 4 inches in diameter will transform to stands whose trees average 6 inches in diameter during the next 10 years. It is unlikely that the 4-inch stands will transform during the next 10 years to seedlings or saplings or to stands whose trees average 20 inches in diameter. Observing the most frequent transformations of plant and animal communities from one state to another led ecologists to the concept of succession.

Succession is viewed here as a special case of transformation of plant and animal communities from one state to another. The important point is that many forest transformations can be predicted with an acceptable accuracy for one or more decades. The validity of these predictions is used to direct ecosystem dynamics. The approach presented here is to use knowledge of ecosystem dynamics to predict transformations after biomass is removed. Biomass is removed, usually by timber harvesting, to bring the forest to a certain state of organization, which is defined as the distribution of stands by stand condition classes. Stand condition classes are defined by age and area classes and by forest types.

Managers and management teams, however organized, are provided a simple and effective tool to systematically provide benefits singly and in different combinations. The new direction uses conventional silvicultural techniques, some of which were developed more than a hundred years ago. The method is not radically new; it is a restructuring of knowledge and technology.

The New Direction

The new direction is to ask and to answer the question: What state of organization do we want for this forest?

Order in forests, also called structure, is the way plants and animals are arranged and connected to each other and to the environment. The concept of organizational state includes these arrangements, distributions, and connections.

A certain state of organization is described by a specified distribution of component parts that are maintained as a dynamic system. For example, a forest may be kept in a state that is defined by the proportion of stands in certain type, age, and area classes. The stands are dynamic in that they are constantly changing from one condition class to another.

Consider a steam engine operating at a constant speed. The state of organization is defined by the proportion of fuel, water, and steam in the engine. This state of the engine may be retained for a long time only by the constant transformation of the fuel, water, and steam from state to state.

The benefits, possibly power, derived from the steam engine are determined by the state of organization. Changing the organizational state--the proportions of fuel, water, and steam--changes the availability of the benefits. Unpredictable or uncontrollable organizational states of the steam engine--and of forest systems--result in unpredictable kinds and amounts of benefits.

The new direction for forestry is to control organizational states of a forest to provide human benefits. The state of organization determines the biological potential for harvesting timber; for hunting, hiking, fishing, camping, enjoying

wilderness conditions; and for conserving endemic genotypes. The new direction uses a knowledge of the dynamics of forest organization to direct organism behavior and provide human benefits.

For management purposes, operational criteria are used to describe the organization of forests. "Operational" means that the criteria can be readily defined, measured, and related to management decisions. Criteria that have been used for many years for both natural and artificial stands are forests types, the age classes of stands, and the area classes of stands. The distribution of stands by these stand conditions describes, for practical purposes, the forest's organizational state.

Structure or organization may be viewed as the way parts of a system are connected. The walls of a building are connected to form spaces for working, cooking, eating, playing, resting, and sleeping. The values of the benefits derived from a building are determined by the arrangement, the interrelation, and the linkage of the walls, floors, doors, windows, and other parts. Different buildings provide different combinations of benefits, primarily because different kinds of parts are structured in different ways. The combinations of benefits available from both buildings and forests are determined by structure.

Different forests provide different combinations of benefits because different kinds of plants and animals are arranged and connected in different ways to form different kinds of stands. Furthermore, forests are dynamic rather than static. The dynamic structure is driven by mortality, which results primarily from the mechanisms of natural selection. Physical mortality associated with natural selection is caused by the inability of individuals to maintain some essential variable within the limits for life.

Essential variables include water content, photosynthesis rate, nutrient absorption, food capture, blood sugar content, and the body's physical integrity. Genetic mortality occurs when survivors fail to transmit genes to the next generations. Both physical and genetic mortality are consequences of the physical and chemical behavior of each organism as controlled by a specific genetic code being translated in a specific environment. Physical and genetic mortality not only influence the kinds and proportions of genes transmitted to the next generation but also organize the structure of communities. Once the genetic code is fixed by asexual or sexual reproduction, physical mortality structures the forests and determines the availability of human benefits for some period of time.

Thus, the biological structure of unmanaged forests and the dynamics of this structure are determined by the processes of genetic mutation, recombination of the genetic code, and natural selection of phenotypes. Both the structure of unmanaged forests and organic evolution are driven by the same biological mechanisms. For the same reasons that organic evolution is aimless, the natural, unmanaged forest is also aimless. In unmanaged forests, future states of organization are uncontrolled; productions of benefits are not directed. This relationship is important for making decisions and taking actions to direct the organizational states of a forest toward a desired state and for producing biologically possible and desired combinations of benefits.

Decision and Control

The typical question forest managers attempt to answer is, "How much timber, water, wildlife, recreation, and wilderness should be made available to users?" This question is difficult to answer because of the complexity of integrating

and projecting more than three or four benefits with an equal number of management actions and because of the difficulty of predicting social, economic, and political changes.

The new direction poses different kinds of questions: To what dynamic state of organization do the interested parties want the manager to bring a forest? What states are biologically possible and desirable? What combinations of benefits are possible? The answer is a single goal toward which all cultural actions are directed. Complexity is constrained. Now the manager can schedule an orderly change in the forest's organizational states, and the biologically possible combinations of benefits can be projected for many decades.

Decision and control uses silviculture as part of a larger management system. Regardless of the interested parties--a large corporate structure, a landowner with less than 100 acres of forest, or a public agency directing the use of millions of acres of public land--the question is always, "To what state do I want to bring this forest?" Implementing the answer requires investments and direction of management resources. The resources used by silviculture are only a portion of the larger management system.

The distinction is not always clear between directing to achieve a silvicultural response and directing to achieve goals of the larger management system. In practice, silviculture must be congruent with the larger management system. The new direction achieves this by integrating decision and control loops (fig. 3). The particular management projections selected become the dynamic plan.

States of a forest are projected by the DYNAST simulator from the present state of the forest, through many transformations, toward a

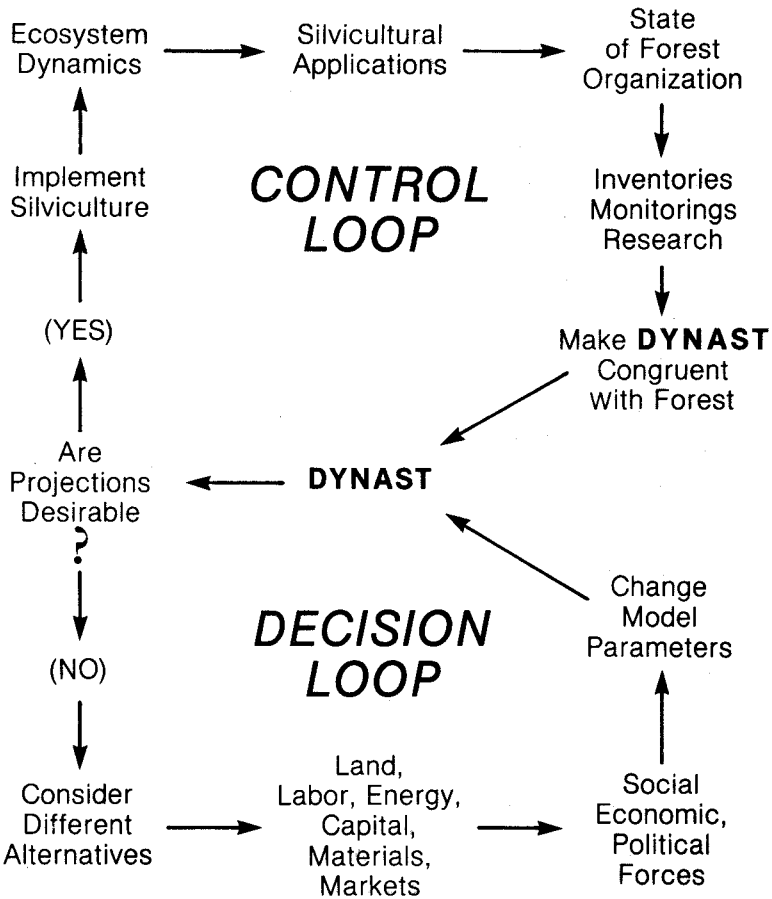


Figure 3.--Structure of the decision and control system for integrating biological and managerial information.

number of alternative organizational states (figs. 4, 5, 6) (Boyce 1977). One state is selected as a goal. The goal is periodically adjusted in relation to socioeconomic and political changes. The projection of benefits through the next decade is important information for choosing a goal. And the ability to periodically adjust the goal provides a way to keep combinations of benefits congruent with socioeconomic changes.

A diagram helps to illustrate the structure of the decision and control process (fig. 3). Information flows in two circular loops--one for decision and one for control. The two loops are linked by a system dynamics model called DYNAST (Forrester 1961). The letters in the mnemonic name come from Dynamic Analytic Silviculture Techniques (Boyce 1977). The DYNAST model integrates data from inventories, monitorings, and research with alternative control variables to simulate benefits and impacts for alternative modes of management. The simulation is an analytic technique that provides information for subjective decisions.

Each loop is constantly modified by external sources of information. New information for the control loop is knowledge about ecosystem dynamics and the use of this knowledge in silviculture. New information for the decision loop comes from social, economic, and political situations that determine the availability of land, labor, capital, markets, energy, and materials. These latter changes also affect opinions and insights that enter into the subjective decisions.

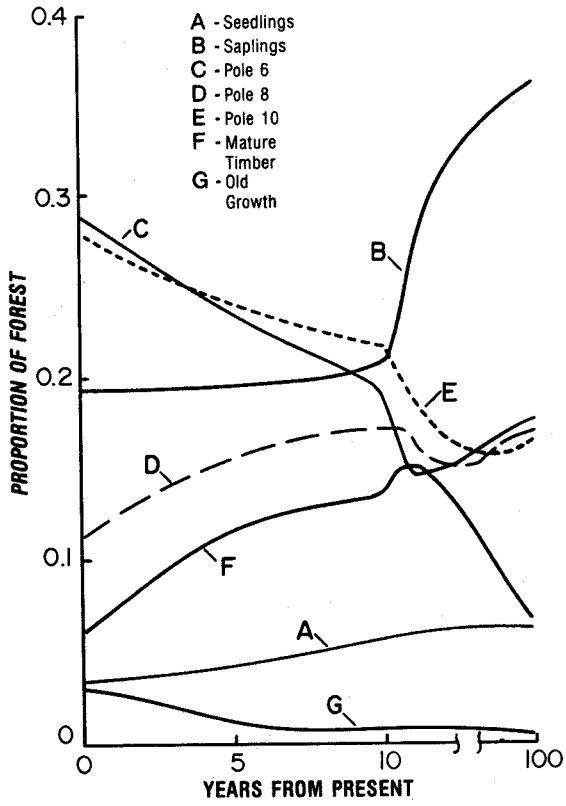
The changing social, economic, and political situation continuously alters the markets for forest goods and services. Each plan is for a brief period, but consideration is given to the much longer effects of silviculture on the basic resources. Viability of the forest ecosystem depends on managers responding to rapid changes in

social, economic, and political forces while sustaining the basic resource values. DYNAST simulates annual changes and long-term effects for the alternatives being considered.

DYNAST simulates transformations from state to state for any forest that can be described by spatial and temporal changes in stands by age class and forest type. The simulation model transforms a forest to a future state in relation to a mode of silviculture. The model is an analytic technique that enhances the decision and control process. The simulation uses information about ecosystem dynamics and silviculture to transform the present state of the forest to the next most probable state.

This analytic technique interrelates quantifiable variables of silviculture, inventories, monitorings, and research with the subjective variables for decisions. Consciously or unconsciously all interested parties are engaged in subjectively perceiving some future benefits from the forest. It is on the basis of these perceptions that commitments are made to invest labor, forest land, capital, energy, and materials to implement silviculture. The actions are designed to transform the forest toward a certain state of organization.

When the management team is given responsibility to implement silviculture for the management mode selected, then land, labor, capital, energy, and materials are committed for a short time. The progress rate in applying silviculture is monitored against the rate used in the DYNAST simulation. Transformations in the forest's organizational state are inventoried. Research adds new knowledge, data, and insights about ecosystem dynamics and about the forest's responses to silviculture. This information is used to keep the model, DYNAST, congruent with the real forest.


A - Seedlings
B - Saplings
C - Pole 6
D - Pole 8
E - Pole 10
F - Mature Timber
G - Old Growth
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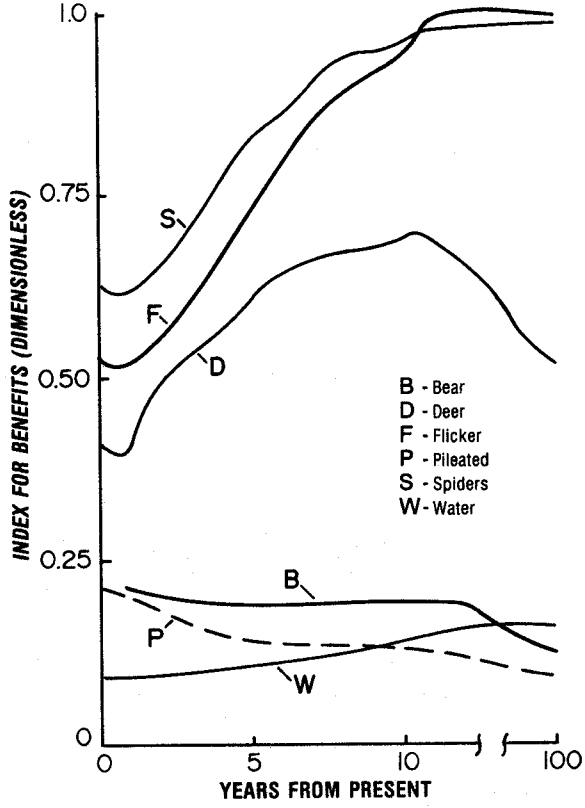
YEARS FROM PRESENT


INDEX FOR BENEFITS (DIMENSIONLESS)
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0.75
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B - Bear
D - Deer
F - Flicker
P - Pileated
S - Spiders
W - Water
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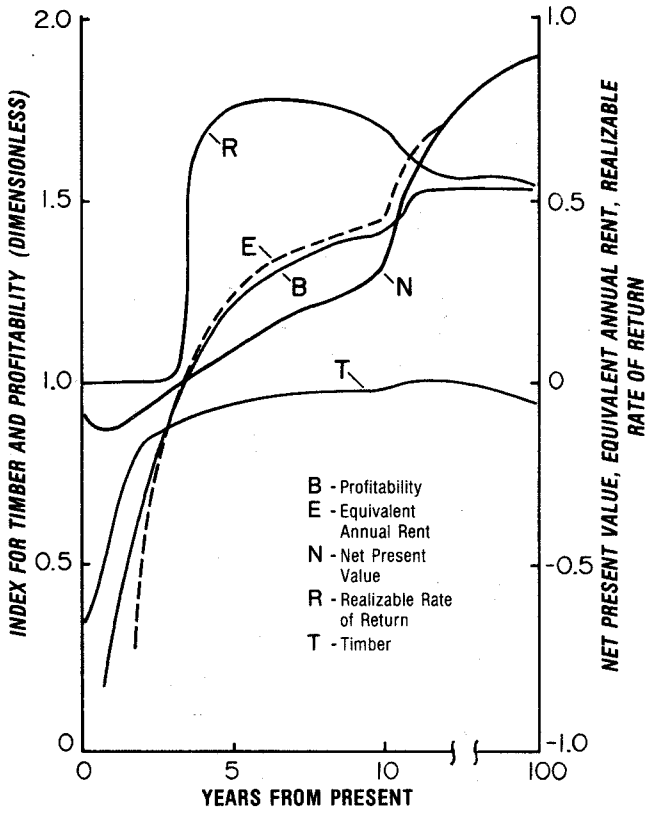
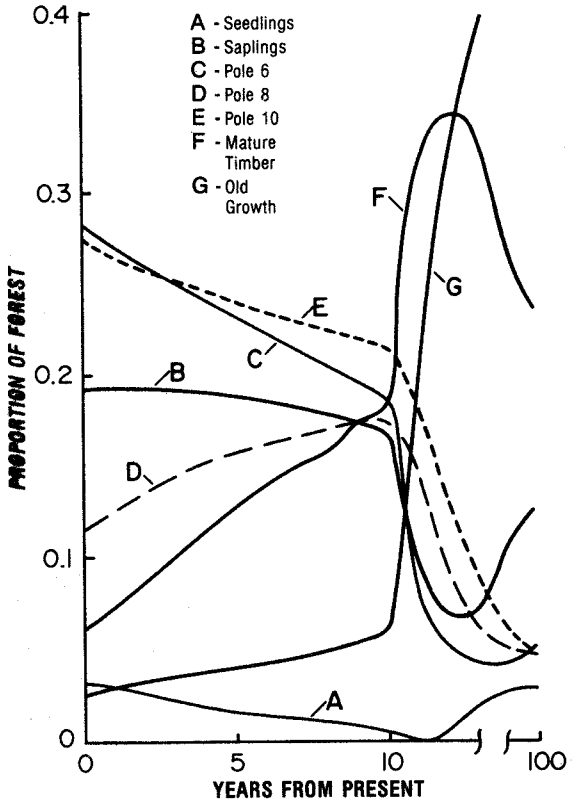


Figure 4.--Consequences of regulating the Big Ivy forest (described in ch. 8) with an 80-year rotation period.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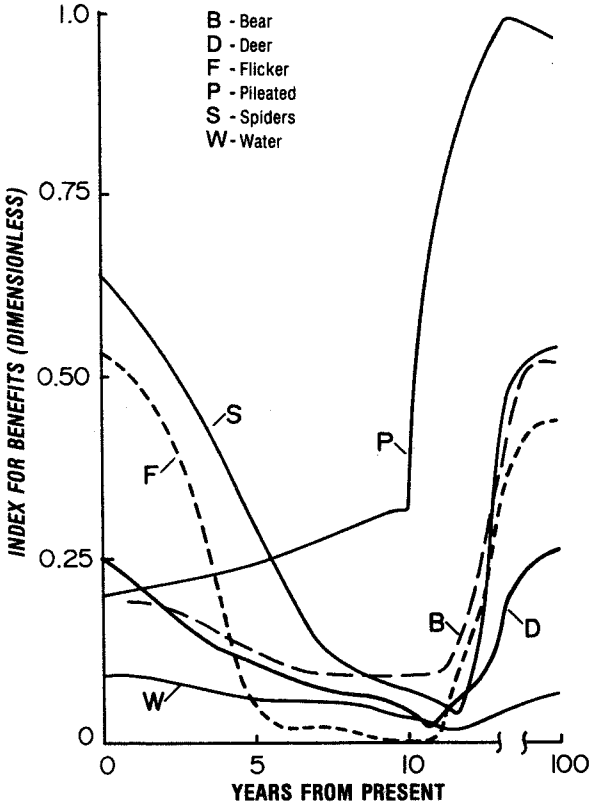
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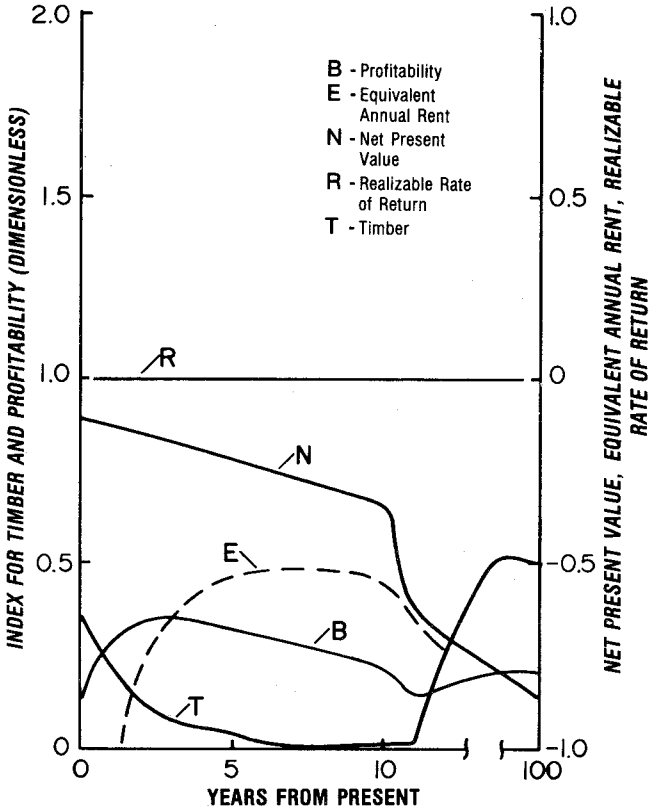
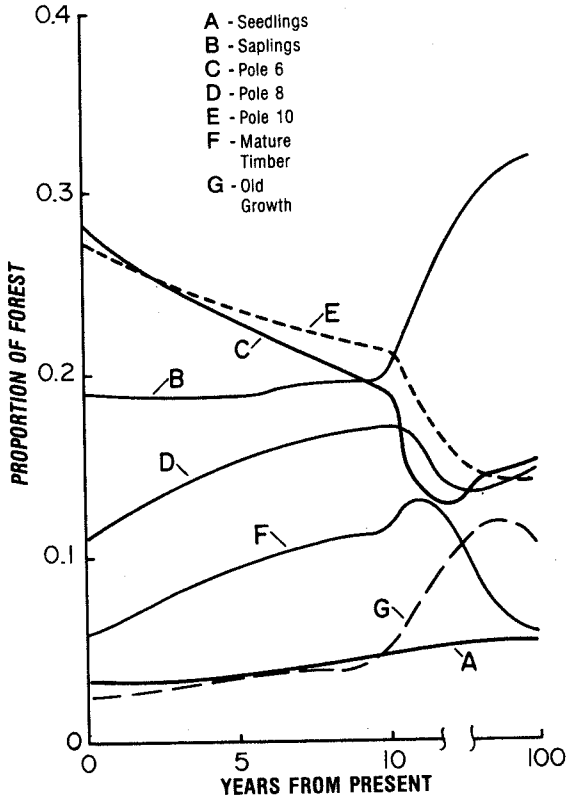


Figure 5.--Consequences of regulating the Big Ivy forest (described in ch. 8) with a 200-year rotation period.


A - Seedlings
B - Saplings
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D - Pole 8
E - Pole 10
F - Mature Timber
G - Old Growth
PROPORTION OF FOREST
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0.3
0.2
0.1
0
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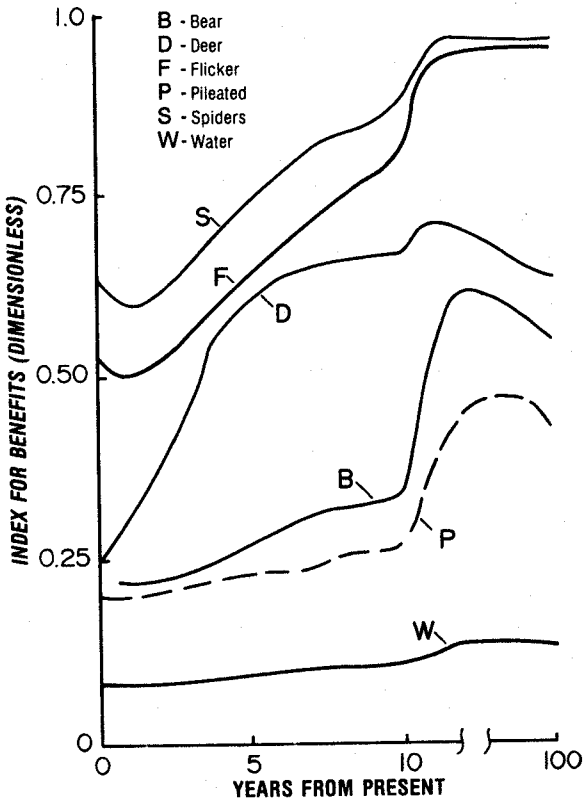
5
10
100
YEARS FROM PRESENT


B - Bear
D - Deer
F - Flicker
P - Pileated
S - Spiders
W - Water
INDEX FOR BENEFITS (DIMENSIONLESS)
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0
5
10
100
YEARS FROM PRESENT

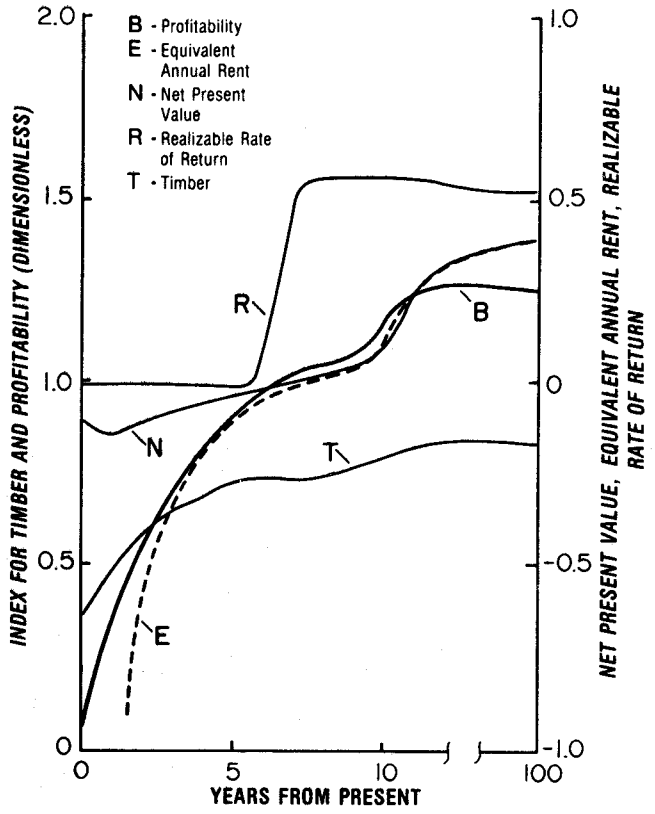

Figure 6.--Consequences of regulating the Big Ivy forest (described in ch. 8) with superimposed rotations; 80 percent is rotated through an 80-year period and 20 percent through a 200-year period.

Also, the management mode may be changed at the end of each planning period, or before if a major change has taken place. For such a change, the simulations provide information about expectations and consequences before altering the real forest.

Management perceptions change in relation to social and economic forces, the availability of management resources, and forest transformations. The situation is continually evaluated by management and interested parties. The combinations of benefits provided and the kinds and rates of investments are adjusted. The two closed loops (Control and Decision) are coordinated and integrated by a dynamic plan that is selected from the simulation alternatives (figs. 4, 5, 6). Adjustments of the dynamic plan keep the loops responsive to new information about social and economic forces and ecosystem dynamics.

The participation of all interested parties depends on communication of explicit information about the decision and control process. The simulations of alternatives are presented in explicit charts and tables. The availabilities of benefits and amounts of impacts are plotted on a common scale of 0 to 1. Differences are apparent from visual examinations. The DYNAST programs are documented. The equations are easy to understand. The relations for benefits are expressed verbally and in simple tables and charts. These relations can easily be changed as new information becomes available. There are no complex matrices and no arbitrary interaction coefficients. The process can be made explicit to all interested parties and all parties can participate in using and choosing alternatives.

The choice of a management mode, one of the simulated plans, is subjectively determined by the knowledge, insights, value judgments, and experience of each interested party. Answers to the question, "Are projections acceptable?" (figs. 4, 5, 6) are derived in the same way that we choose

food or a new pair of shoes. Compromise is an essential part of the decision process. Strong differences of opinion may not be easily compromised, but the possibility for compromise is enhanced by all interested parties participating in posing and choosing alternatives. The biological constraints in the control loop keep the considerations within the limits of biological possibility.

By using this method, cultural practices can be scheduled to provide forest benefits for many decades. The new direction provides for compromise of strong differences of opinion; the integration of data and opinion; the use of interdisciplinary knowledge and technology; the use of a dynamic plan that is responsive to changes in social, economic, and political forces; and constraint of complexity in the decision and control process.

Complexity

The decision and control process is a cycle of three events: (1) assembling information about the state of the forest; (2) using mental models to make decisions; and (3) applying cultural actions (fig. 3). An important difficulty is that information can proliferate to unmanageable proportions in all three events.

First event. Assembling information about forest types, stand condition classes, age classes, trophic classes, biomass classes, soil classes, productivity classes, and similar elements increases the complexity for decision and control. The amount of time, effort, and cost required to systematically assemble an enormous variety of information on the states of a forest and then to consider the ecosystem dynamics in relation to alternative cultural actions is an appalling challenge. The way to reduce complexity is to limit the number of inventory and monitoring

variables admitted to the decision and control cycle. The criterion is to admit only variables that reflect the transformations in states of forest organization. Research techniques are used to identify the essential variables that describe the ecosystem dynamics, develop new cultural practices, and provide knowledge to explain relationships.

No single rule or guide exists for limiting the amount and kind of information admitted to the decision and control cycle. In general, the shorter the cycle, the less data required to keep the dynamic plan congruent with the forest.

Second event. The second event is troublesome because of the difficulty of keeping mental models for the behavior of ecological systems congruent with the real forest and with responses to cultural actions. Mental models are built from experience, insights, personal perceptions, and principles--relations typically derived from a systematic assembly of knowledge. Mental models are communicated in various ways among managers, interdisciplinary staffs, and other interested parties. Communication modifies mental models of participants. Major difficulties among participants are to know what variables to include in explicit models, how to structure the variables to be congruent with the real forest, how to maintain dynamic plans, and how to identify and overcome limitations resulting from the absence of information.

Research, imaginatively conceived to answer fundamental questions about ecosystem dynamics, is apparently the most effective way to limit complexity in the second event. Relations that can be operationally structured and basic principles that apply to an array of life forms can contribute to mental models and lead to simple, explicit models that limit the number of control variables.

DYNAST is an aid for the second event. Large amounts of information are reduced to explicit, simple charts and tables. These charts and tables, which represent projections in relation to actions, help each participant limit the complexity of building mental models and communicating these models in some explicit form. The active participation of all interested parties in changing the control variables permits individuals to communicate with others (fig. 3). Manipulating the DYNAST controls is a good way to aid the structuring of mental models.

Third event. The third event is troublesome because the complexity of silviculture is increased by constant changes in cultural actions caused by social, economic, and political forces. New knowledge from research, monitorings, and inventories must be integrated with silviculture. Sorting and using new knowledge and technology are difficult chores. Attempts to match responses one-to-one with cultural actions can proliferate complexity to unmanageable proportions. A cultural scheme is used here to limit both complexity and the number of cultural actions that must be harmonized in the applications.

The DYNAST technique is to systematically use three control variables--rates of timber harvest, sizes of openings formed by timber harvest, and the conversions of forest types. These are the primary controls used to order the ecosystem dynamics of forests. This orderly way to transform the forest from one state of organization to another provides predictable variables--the temporal and spatial dispersion of habitats--that can be used to project the potential for all forest benefits singly and in combinations (figs. 4, 5, 6).

The DYNAST method is useful because values for only a few variables are needed to predict multiple benefits for alternative cultural actions.

Chapter 2

Structure of the Decision and Control System

Overview

Structure, the way the component parts are connected, determines the dynamics of the decision and control system. For silvicultural applications, the managers in the decision and control system must be able to anticipate organizational states of a forest for a year up to many decades. This is achieved with a feed-forward loop linked with a number of negative and positive feedback loops. These connections orient and schedule information flows that operate through delays, amplifiers, and transducers to simulate states of organization of the managed forest. Benefits are projected by relating each benefit to an organizational state. The silvicultural applications, inventories, research, monitoring, management, and biological constraints are all forms of delays, amplifiers, and transducers (Milsum 1966). All of these elements are components of the decision and control process.

Control Loop

The control loop is structured to give preference to the biological constraints (fig. 3). This structure is essential if the focus is to be on uses within the biological limits for sustaining basic resources. For example, investments of money and labor can only partially control photosynthetic rates, mortality, conversion of carbohydrates to marketable forms of cellulose and game, delays in growth and reproduction rates, and many other elements of ecosystem dynamics. In manmade manufacturing systems, constraints such as marginal costs, marketing, and supply and demand functions can be controlled more than in biological systems. When the production functions are

based primarily on ecosystem dynamics, the biological constraints must be given preference in the control loop.

The control loop must be kept simple. It is not possible to incorporate the behavior of every organism into controls. It is possible to incorporate elements, such as delays and inventory information, that constrain the simulations to reflect the behavior of the real forest. Once these constraints are put into DYNAST, all of the simulations are considered to be biologically possible and within the biological limits for sustaining basic resource values.

Biological theories, hypotheses, and algorithms are adjusted with results from research, monitoring, and inventories. This kind of new information must continually flow into the control loop.

Decision Loop

A management decision is a subjective choice of one plan for some period of time from two or more alternative plans (figs. 4, 5, 6). We do not know how to quantify the choosing process because it involves integration of data with experience, insights, and value judgments. We can quantify and manipulate the data components of the process. Our inability to quantify the subjective components of the decision process is the primary reason for the "Yes" or "No" question following the DYNAST projections (fig. 3). These kinds of decisions are taken by mental processes similar to those used for purchasing a pair of shoes, a coat, and food. These mental processes cannot be modeled and predicted by mathematical techniques such as cost-benefit analysis and linear programming. The decision loop must provide for the integration of these subjective decisions based on an individual's mental perceptions of personal interest. The integration results from directing

the decision toward the choice of one dynamic plan, making the cost and benefits of each option explicit, and giving each party an opportunity to participate in developing plans.

Decisions are often conceived as limited by flows of money, labor, materials, equipment, and capital. These variables are important, but the process of choosing uses insights, value judgments, acumen, experience, and flair. Information that may pass as fact and marketplace values almost invariably are integrations of data and specifications resulting from value judgments. The data are derived from research, inventories, and monitorings. The value judgments are derived from information that originates in social, economic, special interest, and governmental activities. These activities provide the basis for opinion, fashion, reputation, attitudes, and perceptions of self-interest.

The interested parties, one or more people, shift their value judgments about forestry goods and services. As different social and economic forces interact in the larger social system, information from outside the boundary of forestry changes perceptions of self-interest. For example, changes in transportation cost change the values that hikers, lumbermen, and hunters place on a particular forest. Criteria for decisions received by forest managers change because new special-interest groups arise and others decline. Legislative activities change directives for the managers, change public attitudes, constrain public expenditures, and directly and indirectly change the "Yes" or "No" answers for both private and public forests.

Choosing a forestry goal, a dynamic plan to move the forest toward a state of organization, is more like solving a problem in social dynamics than solving a problem in silviculture. The decision taken subjectively integrates the constraints, expressed as value judgments, of the

socioeconomic situation at that moment. In a few years, even months, a different decision may be taken, not because states of the forest changed rapidly but because the state of the external, social, economic, and legislative systems changed rapidly.

It has been argued that the dispassionate analysis of data, the hallmark of scientists, should elevate management decisions above the uncertainties of untried mental perceptions and value judgments (Eilon 1980). Attempts to derive "Yes" or "No" answers with analytic techniques have been unsuccessful for specific segments of some management systems. For example, maximizing or minimizing a single variable such as present value is appropriately determined with linear programming techniques and is appropriate for decisions about investments in land, labor, energy, and materials.

Linear programming can be used to locate roads for harvesting timber, to minimize cost for a technical strategy, and to maximize values from a thinning and harvest schedule. In practically all organizations, these kinds of analyses concentrate on technical strategy (Eilon 1980). This strategy is based on the use of technical knowledge to achieve defined goals.

Science makes significant and essential contributions to the decision and control system (fig. 3). The choice "Yes" or "No" results from mental integration of scientifically and subjectively derived knowledge. The scientific variables aid the choice by reducing complexity, explicitly communicating alternatives for consideration, and keeping the alternatives congruent with the real forest.

A basic concept of the decision and control loop (fig. 3) is to recognize the subjectively chosen plan as a reflection of the aspirations of

the interested parties for forest goods and services. This approach complicates the silvicultural chore because these aspirations require culture for multiple benefits. Yet, culture for multiple benefits appears essential for most industrial forests to produce profits, for non-industrial private owners to achieve personal gains, and for publicly owned forests to provide diverse goods and services. For example, a private corporation seeks short-term profit, but rarely at the expense of long-term disadvantage. A compromise by the corporation is to provide multiple forest benefits in response to the value judgments, opinions, and fashions of interested parties but with due regard to the interest of the shareholders. A forest may be managed for raw materials, industrial jobs, and woody products, but legislative concerns may include constraints for the interest of hunters, recreationists, and other special-interest groups.

Another basic concept of the decision and control loop is: for every statement of a single desire there is a counter desire or biological constraint that prevents the first from being maximized or minimized. For example, a manager can increase total water yield by removing all of the forest, but the cost of erosion, floods, and water during droughts can be greater than accepting a forest cover and a more moderate amount of water in the management scheme. Accumulated volumes of timber can be rapidly harvested without concern for sustained productivity, but the depreciated cost for the long restoration period can be greater than the gain from rapid timber harvest.

The situation is this. Biological constraints are used in the decision and control loop to assure that biologically possible alternatives are considered; basic resources are sustained; multiple benefits and impacts are integrated in biologically possible combinations; the choice of a goal is congruent with the real forest; and

variables of the DYNAST model, especially delays and algorithms for benefits, are constantly updated as new research and inventory information becomes available.

Cybernetic Foundation

Control and communication in biological systems are possible because of structure--the way the component parts are connected. There are many kinds of structure; one type forms feedback loops that direct the behavior of the system to achieve or maintain some goal, such as keeping the level of blood sugar within the limits for life. These loops are negative feedback loops with goals. A negative feedback process is one in which a decision-making process regulates the system by comparing the immediate past conditions with a standard or goal and making adjustments to achieve a steady state (Wiener 1961).

Negative feedback loops make the system aware of its own performance by using outputs to regulate inputs. Algebraic signs can reverse in the decision process. If there is too much, a quantity will be reduced; if there is too little, it will be increased. When this kind of system is disturbed, it typically reacts with a series of diminishing oscillations. A hand reaching for an object moves through such oscillations on a nearly invisible scale. These oscillations illustrate reversals of algebraic sign by which a decision process alters states to approach the goal (Forrester 1968; Milsum 1966).

Other kinds of structure may have no feedback loops or the loops may be positive rather than negative. Positive feedback loops, such as interest rate, tend only in one direction and have no mechanism for reversing an algebraic sign. Systems with only positive feedback loops cannot take corrective action in pursuit of a goal or to maintain a standard. In such systems counteractions

may achieve a sort of balance. For example, the interaction of death rate and birth rate may tend to maintain a population within some limits. However, a system without a goal does not move toward a predictable steady state.

Some concepts for control with negative and positive feedback loops have been known for hundreds of years (Wiener 1961). In the 1940's, the word "cybernetics" was applied to these kinds of decision and control mechanisms in both organic and inorganic systems. During the 1950's the cybernetic principles, primarily from examples in electrical engineering, were broadened to form a system dynamics philosophy for management (Forrester 1961). This philosophy provides the methodology needed for the new direction in forest management because of its cybernetic orientation to a system's behavior and its use of dynamic models to search for flaws in alternatives before implementation.

The most effective decision and control systems include one or more negative feedback loops, positive feedback loops, and feed-forward loops (Ashby 1973; Beer 1966; Milsum 1966). These loops may be viewed as information networks that link the components of a system to form a certain organizational structure. According to the system dynamics philosophy, this structure is the principal cause of the system's behavior. The structure includes the physical components, such as those in the control loop (fig. 3), and the intangible policies, desires, perceptions, insights, and acumen included in the decision loop. These structures contain sources of delays, amplifications, and transformations that generate complex, nonlinear responses to simple input changes. The analysis of these kinds of large nonlinear systems and the design of decision and control methods is the primary use of the system dynamics philosophy.

The analytic approach in system dynamics views organizational behavior in terms of the

flows of information, energy, and materials rather than in terms of functional units. The flows of stands through age classes in a forest, the flows of timber volumes, the flows of wildlife habitats, and the flows of water and nutrients are known to forest managers. The flows of labor, money, materials, energy, capital investments, and markets can be identified in all management organizations. In the system dynamics model, DYNAST, the integrating flows of information link these components to form a time-varying flow structure. This flow structure crosses functional, academic, and managerial disciplines without conflict. This approach dispels the function constraints to decisions and promotes interdisciplinary harmony. All areas contribute equally to the decision and control process.

Recent developments have increased the application of cybernetic concepts for decision and control in management and have improved the quantitative analysis of the flows of information and management resources in organizations. Flaws in the plans may be identified by system dynamics models, such as DYNAST, and by the research, inventory, and monitorings that keep DYNAST congruent with the forest. Simulations may be constrained by limited information and by incompletely validated data. These constraints are inherent in all decision and control procedures, especially for biological systems. They cause inefficiences that are reduced in DYNAST by recursive examination of the data, suppositions, and decisions. What is important is the general usefulness of the interactive, cybernetic approach to policy design. This is the conceptual framework for the new direction.

The initial assumptions and the initial data used in the first DYNAST projections are derived from the literature, personal experience of forest managers, and discussions with persons in many disciplines. After implementing the plan, repeated inventories, monitorings, and research

efforts are used to make DYNAST congruent with the forest and to make the management plan descriptive of past experiences and problems.

Negative Feedback Loop

By definition, control is evident in both biological and inanimate systems. The mechanism in dynamic control systems always includes information networks structured to form one or more negative feedback loops. These kinds of information loops direct the behavior of the system toward a goal that originates outside the information loops (fig. 7).

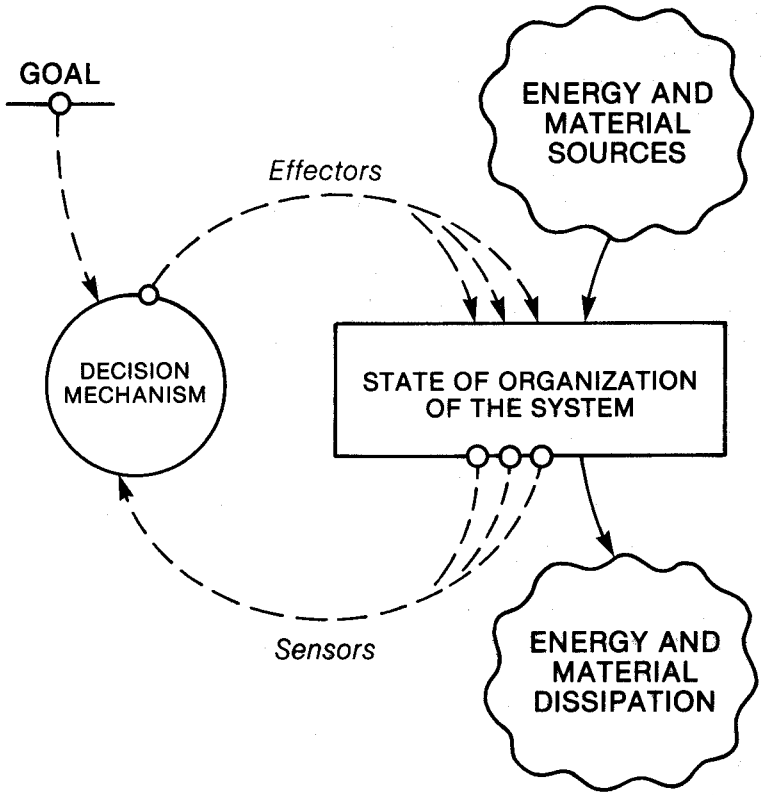

Figure 7.--A negative feedback loop illustrating the structure and flow of information (dotted lines) and materials (solid lines).

Information received by the decision mechanism is compared with a standard or goal that originates from outside the information loop. Once the decision mechanism makes the comparison between the incoming information and information from the goal, the mechanism generates new information that is transmitted as signals to effectors. The decision operating through the effectors may continue or reverse the behavior of the system. For example, if a driver finds the automobile is headed off the highway, the decision may be to change the direction of the front wheels, change the speed of the car, or revert to a number of other forms of behavior. The end result of decisions is to direct the organizational state of the system relative to its preceding state. The flow of information may continue or reverse the behavior of the system to achieve a goal. These kinds of closed loops that continue or reverse behavior are called negative feedback control systems.

Information directs effectors of the system to do something. This is achieved most often by amplifiers that increase the force, the flow of energy, and the amount and duration of change in relation to the very small amount of energy carried by the flow of information. The amplifiers raise the amount of energy used in the system by using another energy source. Muscles are examples of biological amplifiers. The automobile driver implements decisions to change the car's direction by using information flows to the muscles to amplify the force on the steering wheel. Mechanical amplifiers on the car, such as levers and power steering, further increase the forces exerted on the wheels.

Transducers, which convert energy from one form to another, are important parts of the information networks. An amplifying transducer converts energy and raises it to a higher level by

utilizing another energy source. The photosynthetic mechanism is an amplifying transducer that converts and raises diffuse radiant energy to a higher level of chemical energy. In organisms, cells in sense organs are usually amplifying transducers. For example, in olfactory organs a few molecules of a foreign chemical are signals for a cell to use larger amounts of energy to amplify and transform the information for transmission through the central nervous system.

Energy enters the control process as signals and as the capacity to do work. Small amounts of energy carry signals throughout the information network. The amount of work done by these signals is negligible. Although signals may flow with large forces, it is the effectors that amplify the signals with large amounts of energy from outside the information network to change the state of organization of the system. The total amount of energy present is not related to control in the system. Yet, some minimum amount of energy is necessary for the effectors to amplify the signals and change the state of the system. It is the presence and the structure of the information network that directs the system's behavior toward achievement of goals.

In the automobile, control is attained by shaping and connecting the component parts to develop a certain structure. The particular structure is designed to convey information and energy from the driver to the wheels and thus maintain the automobile on the highway. From a control point of view, however, energy in the fuel is recognized simply as another component such as brake linings, axles, ball bearings, nuts, and bolts. Control is always determined by the structure of information channels that direct the flows of information and energy within the system to achieve a goal.

The flow of information in a negative feedback system is through a closed loop. The signals may be forms of radiation, electric pulses, force exerted on a steering wheel, and other forms of communication and work. Regardless of the kind of signal, an essential requirement is the existence of physical communication channels to transmit the signals.

A driver must have access to physical channels of communication that transmit signals about the location and speed of the automobile, the condition of the highways, and the location of other automobiles. The sensing mechanisms in the human body constantly feed information to the central nervous system, which is the decision mechanism. The central nervous system compares the incoming information with a number of standards and goals such as the delay for stopping the car and the speeds for negotiating curves. Many negative feedback loops are involved in this process. Decisions produce information that is channeled to the effectors such as muscles in the driver's body, the steering wheel, the foot pedals, and other components of the automobile. Control of the automobile is brought about by the flow of information through structured networks within the driver-automobile system. A goal, such as to travel from one place to another, originates outside of the control system.

The sensing mechanisms are not a part of the control system. The information sensed and transmitted always describes the immediate past, not the future organizational state of the system. The future state is perceived in the decision mechanism. The automobile driver knows about a hole in the highway because of current information received by the eye. It is very important for the design of monitoring and inventory methods to have current information used in control systems. Delays in informing the decision mechanism of the system's present organizational state may cause the system to fail.

The dynamic behavior of negative feedback systems compensates, within periods of delay, for deviations of the system from the desired goal. The current state of the system is compared with the desired state and the effectors are instructed to bring performance closer to the goal in the next time interval. The available information about the system's present state is the basis for the current decision that controls the system's behavior during the next moment of time. These kinds of systems actively compensate to maintain a particular state of organization, a goal, in relation to disrupting forces from the external environment.

Feed-Forward Loop

Feed-forward loops are characteristic of anticipatory control systems (fig. 8). Automobile and truck drivers use feed-forward decisions in attempts to maintain a desired highway speed. Consider a heavily loaded truck going down a hill on an open highway. The driver can see in the distance, or remembers from past travel, that soon the grade will change and the loaded truck will be climbing a steep hill. The driver presses the accelerator and feeds forward information to the engine before the truck begins to climb the hill. The driver anticipates the need to make a control decision before the truck is slowed on the upgrade. With feed-forward decisions, a more desirable speed is maintained than with the negative feedback loop only. Thus, decisions in feed-forward systems are based on predictions of future states rather than on information sensed from present states as in negative feedback loops.

Feed-forward loops require humanlike intelligence. They have mechanisms and processes to project future states and to adjust behavior accordingly. Simulations are often useful both for projecting and for determining appropriate response.

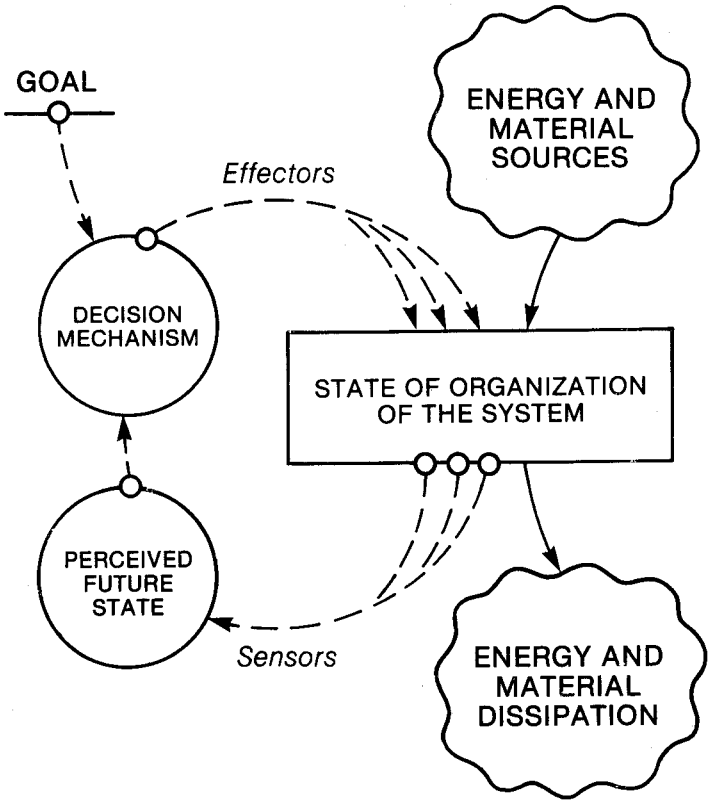

Figure 8.--A feed-forward loop illustrating the structure and flow of information (dotted lines) and materials (solid lines).

Feed-forward loops are limited by human abilities to project the dynamics of systems into the future. Projected future states of the system are used to make decisions and to take actions for control several years into the future. Feed-forward loops are a part of the structure for the decision and control process (fig. 3).

The DYNAST model is formulated to simulate future states of forest organization in relation to silviculture. This model includes nonlinear time-varying functions, control functions, and

vectors for age and area classes of stands by forest types.

Algorithms for benefits and impacts are linked to the simulated organizational states, which are the core of the model. As the simulated forest transforms from state to state, the future availability of benefits and the potential for impacts are computed. A display of these potential benefits and impacts is used to choose the goal, which is a particular organizational state. The DYNAST model is the mechanism that aids interested parties to perceive future states in the feed-forward loop (fig. 8).

When the predicted benefits and impacts are undesirable, a different organizational state is considered. This is done by changing the rate of harvest, the size of openings formed by harvest, the species, or all of these.

A problem of feed-forward loops results from errors introduced into the decision mechanism by inaccurate perceptions of future states (fig. 8). These errors are kept to a minimum by frequent monitorings, periodic inventories, and constant research. This interactive procedure is an important part of the decision and control structure (fig. 3).

Positive Feedback Loop

Control systems may include information networks structured to form one or more positive feedback loops. These loops differ from negative and feed-forward loops in that change is always in one direction. Positive feedback loops are often called density dependent because the loop has no goal and the response rate is related to an existing amount of something (fig. 9).

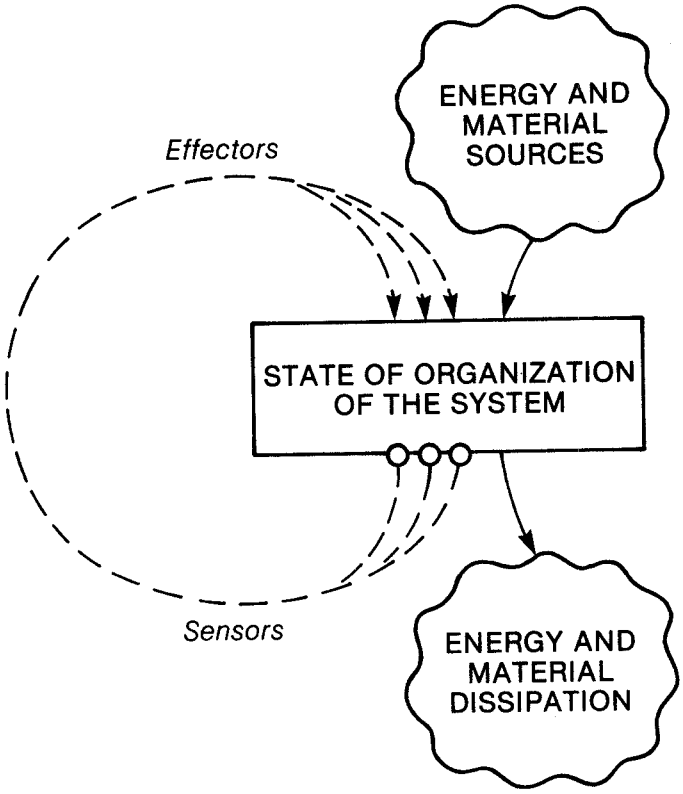

Figure 9.--A positive feedback loop illustrating the structure and flow of information (dotted lines) and materials (solid lines).

Compound interest on funds in a savings account is an example of a positive feedback system. Assume a constant interest rate; the larger the amount of the fund, the more interest is paid at succeeding time intervals. The positive feedback loop does not change the interest rate or the organizational state of the system to achieve some goal.

Positive feedback loops have no goal. Such systems continue to increase or decrease something, always in one direction, until some force

outside of the system changes the state of organization or until materials and energy are depleted.

An example of a positive feedback loop depleting something is the depreciation of a mortgage with constant annual payments. As the mortgage decreases in size, the amount of the annual payment allocated to interest decreases and the amount allocated to principal increases. This system does not have a goal, such as to pay a certain amount of annual interest or to maintain some amount of mortgage. The system functions until the mortgage is depleted or some force outside of the system changes the organizational state.

Positive feedback loops by themselves are not efficient ways to direct the behavior of a dynamic system. When only positive feedback loops are used for control, the system must be constantly monitored and periodically adjusted from outside. The number of positive feedback loops must be matched with an equal number of monitoring and adjustment mechanisms. If more than about three loops are used, the complexity proliferates to unmanageable proportions.

Complexity can be reduced by linking positive feedback loops to negative feedback loops. This is the typical way positive feedback loops are used to develop forest management plans.

A clock is a good example of a positive feedback system linked to a negative feedback system, a person. Energy from the spring or electricity source moves the hands of the clock forward and provides the display of time as an output. But the input of energy and the state of the clock are not affected by the output; the clock has no mechanism for sensing its own performance or its organizational state and cannot take corrective actions in accordance with a goal. If the clock is running fast, it will increasingly deviate from the standard time. Past states do not control

future states, even though the states (positions of the hands) are repetitive. The clock becomes a part of a negative feedback process when a person adjusts the speed control device. A person compares the clock's performance with a standard and decides to take corrective action by retarding the speed. Later, the person evaluates the performance again and takes further action, probably making smaller corrections. The system--composed of a clock and a person--oscillates and gradually reaches the goal, which is the display of time within acceptable limits of error.

Cybernetic Structure for Directed Systems

An automobile and a driver form a directed system that responds to changes in the environment (fig. 10). The mechanical parts, energy source, and driver are structured to form a physically identifiable and functioning system directed toward a specific goal. The generalized goal is survival in moving from place to place. The system transforms from state to state in relation to the external environment. For example, the speed of the automobile changes in relation to curves, holes, and other cars on the road. The thickness of the tires, the friction of the moving parts, the attitude of the driver, and the environment are constantly changing.

The system's environment consists of the forms of energy, materials, and information that influence transformations in its states. Radiant energy from the sun may change the temperature of the car and the driver; a nail may deflate a tire; and water in the cooling system and water as rain may influence the temperature of the engine, the driver, and the car. An internal and external environment may be defined for convenience. In reality the environment is an inseparable part of the system. Operational definitions are used to classify situations such as determining when a

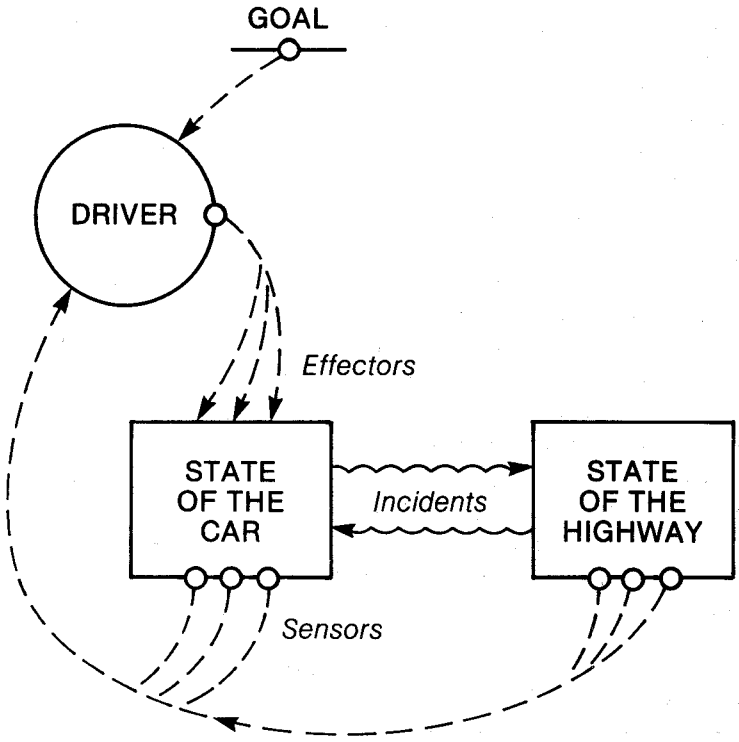

Figure 10.--The structure of the information network for a directed system for a driver, car, and highway. (Dashed lines represent the information loops.)

molecule of carbon dioxide is part of an organism, part of the internal environment, or part of the external environment. Energy, materials, and information not known to influence the dynamics of the system are often not considered parts of the environment of the system.

A goal is part of the cybernetic structure of a directed system. Goals are adjusted with changes in the environment of the directed system. Thus, the dynamics of systems cannot be precisely projected into the future. For example, the driver can identify a destination and even the

sequence of roads to travel, but many unexpected events such as traffic, storms, and stoplights cannot be specified. The directed system self-organizes to survive the trip because of the cybernetic structure.

The cybernetic structure for a directed system consists of sensors, a decision mechanism, a goal, effectors, and most important, an information network that links these elements. In reality, most systems consist of many interlocked, negative, feed-forward, and positive feedback loops. These loops are interlocked such that decisions in different loops contribute to the system's survival. For example, the automobile engine, the gears, the brakes, and the orientation of the front wheels must maintain essential variables within certain limits for the driver to control the speed and direction of the car.

A break in a critical part of the communication network can make the system aimless. For example, a sudden fog can disrupt communications to the driver, or a break in the steering mechanism can destroy the system. A physical communication network that links sensors, effectors, decision mechanisms, and a goal are essential for the cybernetic structure of a directed system. The absence of any one of these elements makes the system aimless.

The driver of an automobile is an important component of the decision and control process. The driver is not an outside manager of the automobile but rather a part of the dynamic, directed system. He is linked to various parts of the environment and the automobile by physical channels of communication. Through these channels, information flows to and from the driver. These information flows control the behavior of the automobile, direct the flows of energy, and maintain the continued existence of the system.

The automobile, the highway, and the driver are linked by a number of information loops (fig. 10). Sensors, such as eyes and ears, inform the driver of the organizational state of the automobile and the highway. The integration of this information, relative to a goal, results in decisions. From these decisions, information directs the transducers and amplifiers to change the state of the automobile relative to the state of the highway.

The state of the car is affected by many variables, but only a few variables such as location on the highway and speed need to be constantly monitored. A small number of control variables such as the steering wheel, brake pedal, and accelerator are required to change the system's organizational state. An important consideration is that the human element in the control process manipulates, with a small number of controls, a complex system.

The forest manager, the forest, and the environment form a directed system with attributes for decision and control similar to those of the driver and the automobile (cf. figs. 10 and 11). Forest managers and interested parties are viewed as integral parts of the decision and control mechanism. The forest manager is not an outside director. The fate of the forest may affect the fate of the forest manager and other interested parties in the same way that order, disorder, continued existence, or destruction of an automobile may affect the fate of the driver and the passengers.

Although the state of the forest may change more slowly than the state of an automobile traveling a busy highway, characteristics for control of the two systems are similar. The forest manager, like the automobile driver, can manipulate only a limited number of variables. Thus, forest

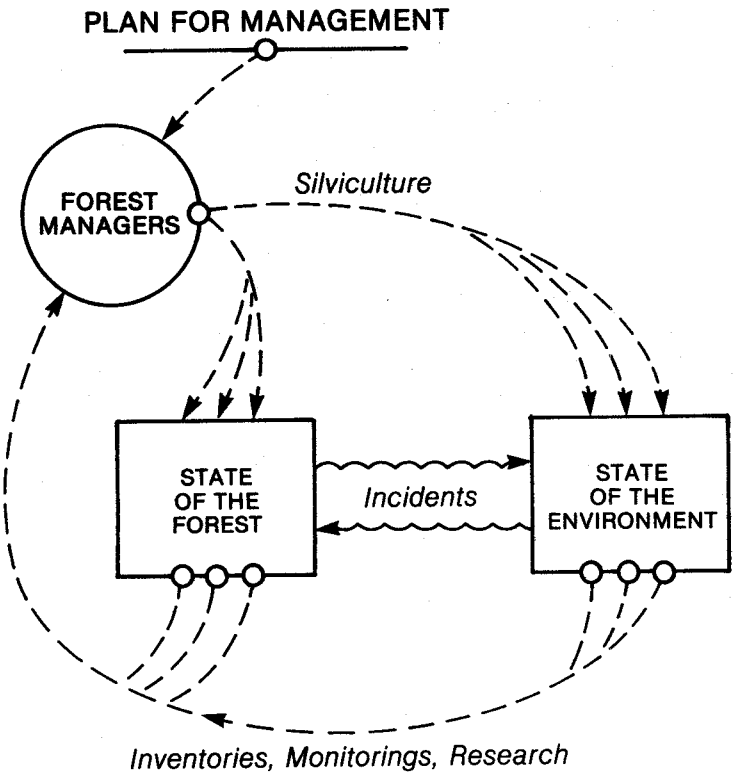

Figure 11.--The structure of the information network for a managed forest system for forest managers, the forest, and the environment.

inventories and monitorings for control should include only the elements required to describe important transformations of the system. A limited variety of information should be admitted to the communication channels for decisions and control. In this way the control variable for the forest can be limited to a small number of silvicultural actions, such as harvesting timber, controlling the size of openings, regenerating openings, and changing forest types.

Many silvicultural actions to enhance the structure of specific stands are most effectively

planned and applied as heuristic decisions. Because of many uncertainties, automobile drivers cannot plan the times to apply the brakes and the accelerator for all stoplights expected on a trip. Likewise, uncertainties limit the planning for many cultural actions such as thinning, weeding, pruning, and fertilizing. These kinds of cultural actions are heuristically adapted to specific stands and are incorporated into the cybernetic structure for in-place decision and control (fig. 3).

Direct controls for the car are the steering wheel, brakes, and accelerator. Activities such as changing the oil, adjusting the carburetor, and inflating the tires are secondary controls. Direct controls for a forest influence the differential mortality rate by species, size, and age classes. The most important direct controls are harvesting some form of biomass, regulating opening size, and changing species composition. Secondary controls are modifications of the environment, such as adding fertilizers and draining wet areas.

Interactions between the automobile and the environment and between the forest and the environment are important considerations. The temperature of the environment affects starting and cooling rates of the automobile, which in turn affect the environment by radiating heat and emitting compounds of carbon and nitrogen. Similarly the environment affects the physiology of forest organisms. These organisms, through their behavior, change the environment by producing dead organic matter and emitting compounds such as water, oxygen, organics, and carbon dioxide.

Interactions between the environment and the forest are outside the dynamics of the system. They are not controlled by flows of information, decision mechanisms, and goals. There are no

known physical, information channels structured as negative feedback loops that direct the environment to provide radiant energy, nutrients, rain, and other materials in relation to the state of forest organization. No information networks exist that regulate emissions of plant and animal compounds through negative feedback loops to bring the environment to a certain state.

The human element plays another important part in cybernetic structure for the directed forest--the development of a plan (fig. 11). The dynamic plan describes the goal and the purpose of management. It originates outside the system as do goals for all negative feedback loops. External forces, especially those related to economic, social, and political situations, determine and modify the goals for forest management.

Concept of Dynamic Plans

The word "dynamic" is used in the sense of changing. This definition is not far removed from the original meaning of power because systems typically change only as a result of forces acting upon them. All biological systems are dynamic because of the nonequilibrium, energy-sorting, and energy-dissipating activities that maintain life. Biological systems, whether of forests or organisms, do not change to a constant level instantaneously after a sudden "step" change such as the death or harvest of dominant trees. After a sudden "step" change, the characteristic dynamics of living systems is a perceptible delay followed by transitions to a new state.

Biological systems of both individuals and communities have irreversible dynamics. Step changes, such as harvesting a stand, change the plant and animal community to a different stand condition class. After a relatively short period of time, a natural succession through a series of

stand condition classes transforms the area. These transient changes create classes that may be called successional stages. Such changes may bring a stand now classed as "mature" to a seedling successional stage after the stand is harvested. This new stand will differ from the original in the proportional distribution of individuals by species, in the location and size of individuals by species, and in the genetic composition of genotypes. The new stand may approximate the harvested stand in many superficial ways, but the original stand is not repeated. Repetition does not occur because there are no negative feedback loops, at least there is no evidence for them, with goals for bringing ecosystem dynamics and natural evolution to some steady state.

Exact projections of structure and behavior are not possible. Nevertheless, repeated observations of the transformations from one state to another can lead to some likely suppositions about the future. We know what kinds of transformations have the highest probability of occurrence and can be most easily directed. For example, when a stand of hardwoods is harvested, the area will normally regenerate in hardwoods that will transform through size classes at a rate that can be estimated on the basis of experience.

Biological systems typically display complicated response patterns to simple management actions such as timber harvesting. If we are to change a forest from some original state to some desired state at a future time, it is necessary to develop dynamic plans in which simple management actions can direct the dynamics of the system. The dynamic plan is examined at least every decade. Harvest rates, expressed as rotation periods, are changed in relation to the organizational state of the forest, the uses desired, and the social, economic, and political situation. The goal is a desired state of forest organization, which may or may not be achieved.

Dynamic control requires that timber harvest be scheduled each year for the planning period, usually one decade. Each year's harvest is related to the rates of dynamic change of the habitats as determined by delays for biological changes. As the forest approaches a desired state of organization, the annual harvest rates may approach a steady state.

With dynamic planning, decisions are used to guide the forest toward a goal. For example, we can identify a distribution of habitats as a goal many decades into the future. We cannot specify where each habitat will be or the number of each kind of plant and animal in each habitat. We can identify an amount of timber expected to be harvested in the next decade, but we cannot specify how much timber will be harvested. The method for dynamic plans is to make decisions, i.e., change the goal (fig. 3) at 5- to 10-year intervals in relation to changes in social, economic, and political situations. Behavior-correcting feedback loops keep the manager and forest system oriented toward the goal while currently producing benefits.

Chapter 3

Ecosystem Dynamics

Overview

A knowledge of ecosystem dynamics is important for predicting forest transformations from state to state in relation to silviculture (figs. 4, 5, 6). In this chapter, operational criteria (Benjamin 1955; Bridgman 1927) are used to develop four bionomic theories (Boyce 1978b). The theories are used to frame the mental and physical models, which are the bases for decision and control. The models are derived from flows of information sensed from the real world. Application and validity of the theories and the models are found by an analysis of the operations performed in concrete situations. For example, the application and validity of a measure of temperature is determined by the sequence of operations that manipulate the thermometer. With operational criteria and theory from physics, the flows of information sensed with the thermometer may be used to form a model for explaining temperature changes. The bionomic theories reduce the dynamics of ecosystems to a description of human perceptions of the actual happenings, give the mental perceptions of one person a frame for comparison with experience by others, and help to reduce mysticism in both experiences and mental models. The theories are a frame of reference for mental models.

Mental models are dynamic perceptions of the immediate past states of a system and mental projections of future states in relation to information flows. Mental models are validated by a frame of reference to what is accepted to be "true," to past experiences, to information derived by others, and to implied and explicit theories for behavior of the system in question. The bases for decisions are one's mental models, which are dynamically adjusted to the information

flows. Thus, most mental models, such as "I am hungry," are transient bases for decisons, such as "purchase this food." Rational decisions, those that maintain essential variables within the bounds of a goal, are guided by a frame of reference for validating the mental model (fig. 7). Mental models are communicated in physical forms such as diagrams, equations, words, maps, and other signals. It is this frame of reference in the cybernetic structure (see ch. 2) that determines the behavior of directed systems. The bionomic theories are the frames of reference that (1) aid our understanding of ecosystem dynamics and (2) guide the use of information for decisions.

The operational approach provides for theories that are constantly challenged by applying the operations and by hypotheses for falsification. Theories are modified by each additional element of knowledge that meets the operational criteria of being physically identifiable, measurable, and meaningful for decision and control. The theories are restated from Boyce (1977):

1. Each living organism and its environment form an individualistic system with the goal of survival and the dynamics of systems with negative feedback loops.

2. The mortality of individualistic systems organizes survivors into communities without goals and with the dynamics of systems without negative feedback loops.

3. The flows of energy, nutrients, carbon dioxide, water, and organic materials are unidirectional and have the dynamics of systems without goals and without negative feedback loops.

4. The states of forest organization determine the kinds and proportions of multiple benefits available from a forest.

The practical use of the theories is to design management schemes that will direct self-organizing, individualistic systems to bring about desired states of forest organization.

An Operational Definition of Ecosystems

The word "ecosystem" was defined by A.G. Tansley (1935). The concept "ecosystem" is appealing because it is holistic and includes all of the physical, chemical, and biological elements of the universe. Tansley said that ecosystems ". . . are of the most various kinds and sizes. They form one category of the multitudinous physical systems of the universe, which range from the universe as a whole down to the atom."

Tansley's operational method was ". . . to isolate systems mentally for the purposes of study, . . . whether the isolate be a solar system, a planet, a climatic region, a plant or animal community, an individual organism, an organic molecule, or an atom. Actually the systems we isolate mentally are not only included as parts of larger ones, but they also overlap, interlock and interact with one another." Thus, the words "organism," "community," "forest," and "stand" are operational definitions of ecosystems as used by Tansley. A specific community, organism, forest, and stand are isolates that we can identify to study and manage. These units include all of the organisms and the organic and inorganic components of the communities and the individual and its environment. According to Tansley, the ecosystem includes "constant interchange of the most various kinds within each system, not only between the organisms, but between the organic and inorganic." These interchanges and flows of energy, materials, and organisms are the dynamics of the ecosystem.

Tansley's (1935) operational analysis reduces ecosystem dynamics to a description of human observations, measurements, and operations. This approach avoids giving ecosystems metaphysical and idealized properties, such as indicated by the term "complex organism." Terms such as "species," "succession," "habitat," "climax," "stability," "biome," "forest," and "stand" are defined by the use to which the terms can be put. For example, Tansley (1929) defined succession relative to use: ". . . the actual value . . . of the concept of succession . . . is measured by the use to which it can be put, to its success in enabling us to focus on phenomena more successfully, and thus to discover new starting points for fresh investigation."

Another advantage of the operational approach is that it reduces ecosystem dynamics to human perceptions of actual happenings and provides for validating actual experiences by repeating the operations used to define a term or concept. Organisms were observed by Tansley (1914) to live as individuals and as part of a system consisting of all those elements, physical and biological, that could conceivably affect the organisms. Cowles (1901) took this same view when he described succession on sand dunes near Lake Michigan. Succession is the change Cowles measured (Cowles 1901:108).

Adams (1908) used Cowles' operational approach to define ecological succession of birds and other animals. Cooper (1926) also used this method to document observations of ecological succession for long periods of continuous change. Cooper (1926), Gleason (1939), and others (May 1976) have also used this approach to describe the individualistic concept of plant and animal communities. And this operational approach led to rapid advances in quantitative methods (Southwood 1978).

In science, the changes from using properties to using operations for defining terms and concepts was apparently brought about by a change from a Newtonian to an Einsteinian approach (Benjamin 1955). The convention is that terms and concepts be defined by physical operations rather than by properties. This viewpoint is accepted by most scientists. For example, according to Newton, simultaneity was an absolute property of time, which he defined as that which has the property of flowing uniformly independent of material happenings. Einstein introduced the idea that simultaneity in a system, and time, is relative to the operations of the observer rather than a property of the system (Bridgman 1927).

For ecosystem dynamics the change is from studying plant and animal communities as defined by idealized properties, such as the organismal concept described by Phillips (1934, 1935), to studying operationally the dynamics of structure and the functioning of individuals in their natural surroundings as described by Tansley (1935) and Evans (1976). The change is from defining organisms and communities in terms of properties, such as a kind of strategy that directs behavior toward a predetermined state or structure, to defining organisms, communities, and behavior in terms of the operations of the observer.

Ecosystem dynamics are the time-changing flows of organisms, materials, and energy that form the units we operationally isolate to study and manage. Organisms, their inseparable environments, and aggregates of these systems are operationally called ecosystems as defined by Tansley (1935). These individualistic systems, populations, stands, and communities are the units most frequently delimited as ecosystems for management.

Three Elements of Ecosystem Dynamics

Three kinds of observations based on experiences of many people are the primary sources of information for developing the four bionomic theories used in DYNAST. These are observations of the continuity of biological change, the irreversibility of biological changes, and the relation of these changes to the structure of the organisms and the environment.

Continuity

The continuity of biological dynamics is so much a part of our everyday operations it is difficult to believe we are experiencing anything significant. From experience we accept the transformation of babies into adults and acorns into oak trees rather than into chickens. Important implications are in the observation: a biological system cannot pass from one state to another without passing through all the intermediate states that are subject to the same processes of growth and mortality.

This observation of biological dynamics known as the law of continuity is restated in mathematics. An important characteristic of continuity in both mathematics and biological systems is that each succeeding state is dependent on the preceding state. Forest stands and organisms do not randomly jump from state to state; each succeeding state is dependent on the preceding state.

Through the use of operational definitions and measurements, we can project the direction and often the rate of transformation. For example, if a tree has a diameter at breast height (d.b.h.) of 6 inches, the projected transformations are for the tree to either die or increase in diameter. The tree is not expected to shrink.

Projecting a series of successional states from retired cropland to forest depends on the continuity of ecosystem dynamics. The measured species composition of one state of a community can be used to suggest and possibly project the next state of species composition. Observations of the continuity of biological change are used to project future states of ecosystems.

Irreversibility

Few people expect to find Ponce de León's Fountain of Youth. People do not transform from adults to children to babies. The photosynthetic process in green plants is not reversed by turning off the lights or limiting the amounts of carbon dioxide and water. Respiration is not the reverse of photosynthesis. Reproduction is not the reverse of death. Regenerating a forest stand is not the reverse of harvesting. Ecosystem dynamics are irreversible.

The natural succession of retired cropland from grass to forest is irreversible. Should the land be converted again from forest to cultivated land for food crops and be retired again from agriculture, the biological system would not reverse but would again transform from grass to forest. The second series of transformations would not be identical to those of the first. The species composition, gene frequencies, and components of the environment are different for each state in both series of transformations.

Structure

Athletes change their bodies from state to state to outplay others because of the way bones, muscles, nerves, and other components are connected. Structure of human hands permits behavior different from the feet of monkeys. Injuries and diseases, especially those that change linkages in the central nervous system, limit behavior. Structure determines ecosystem dynamics.

Organisms are typically defined by discontinuities. Genetic discontinuities, such as those within and between interbreeding populations, may be operationally measured by differences in the chemical and physical structure of genes and chromosomes. Morphological discontinuities are criteria for assigning a plant or animal to a species. The taxonomic decisions result from the operations one performs to measure morphological and genetic differences. Assigning two individuals to the same species is relative to the observing system, a person trained in systematics.

Operational criteria are also used to define and measure forest types, communities, sites, stands, and other aggregates of plants and animals. The discontinuities for these classifications are determined by structural differences. Classifications based on structural differences are meaningful because structure determines ecosystem dynamics. For example, the behavior of a food chain depends on structure that is defined by the proportion of individuals by species, their environments, and how these component parts are linked.

Structural changes in an ecosystem will change behavior: thinning a forest usually changes growth rates of residual trees; changes in the species composition of a stand change the habitat for some plants and animals; and changes in the age classes of stands change the potential livelihood for some plants and animals. Changing gene frequencies by artificial selection changes plant and animal structure for agriculture, pets, and sports. Changing the ecosystem structure directs ecosystem dynamics for human benefits.

If forests are to provide sustained multiple benefits, they must be managed as negative feedback systems with a goal and with the potential for one or more steady states. To attain this, forest management must be compatible with the

dynamics of natural forests. Theories, validated by potential falsification (Becht 1974; Popper 1962), can describe the structure of the biological system and thus provide the standards, the principles, and the guides for analyzing silvicultural options. Such theories are the frameworks for rational decisions. Following is a discussion of four bionomic theories.

Four Bionomic Theories

Individualistic Systems

> **Each living organism and its environment form an individualistic system with the goal of survival and the dynamics of systems with negative feedback loops.**

The goal of survival is described by Slobodkin (1975) as "permitting the organism to continue in the game." The analogy is to the gambler's "ruin game" in which the payoff is to continue in the game as long as possible. The players self-organize in relation to the state of the game; each player is an individualistic system.

Behavior is directed by a decision mechanism. This mechanism is genetically and environmentally determined and is part of the physiological, anatomical, and morphological structure of the individualistic system. Each individualistic system senses and reacts to its own state and uses past or present states to influence actions to adapt to the environment.

Conrad (1979) defines adaptability as "ability to continue to function in the face of uncertainty." Conrad proposes that a reasonably objective measure of maximum, allowable, environmental uncertainty for individual organisms is

death. This is another way to say that death occurs when a feedback loop fails to maintain an essential variable within the limits for life.

The epic of adaption plays itself out, according to Swartzman (1975), in a multi-dimensioned environment. The frame of reference for individuals must be the set of environmental variables, the everyday variations, and the uncertainty of perturbations. Self-organization in unpredictable, multidimensioned environments is the way organisms attempt to maintain essential variables within the limits for life through all stages of development. Those individualistic systems that survive through the reproductive stage may transmit genes to succeeding generations. The actual rate of gene transmission may be modified by fecundity and uncertain events during the reproductive stage.

For all individualistic systems, including the large numbers that die before the reproductive stage, the negative feedback loops self-organize the system in accordance with the goal of survival. This is not a new theory but a very much condensed restatement of the model of organisms developed by Darwin and modified by others (Becht 1974; Gleason 1939; Machin 1964; Tansley 1914, 1935; Waddington 1970). This theory is the foundation of the other three bionomic theories. The dynamic behavior of individualistic, goal-seeking organisms of diverse structure determines the organization of the forest communities and the transformations of these communities from state to state. The individuality of these systems and their goal-seeking behavior cause every individualistic system to develop differently from every other individualistic system. Thus, in forestry, tree mortality cannot be predicted except as a statistical probability for a population in some specified state or community organization. It is difficult to predict which individual seedlings will live in succeeding states.

Mortality, like other forms of behavior, results from the dynamics of individualistic systems. Death occurs when a feedback loop fails to maintain one or more essential functions, such as respiration, circulation, food consumption, hydration, or physical integrity, within the limits for survival. Failure in a feedback loop may result from changes in the environment or failure in the structure of the individualistic system. This mortality, resulting from the dynamics of individualistic systems, organizes the forest community. In the words of Tansley (1935), "Though the organisms may claim our primary interest, . . . we cannot separate them from their special environment, with which they form one physical system." Each organism and its inseparable and special environment is viewed as an individualistic system uniquely different from all other individualistic systems. And the state of each system changes with migration, age of the organism, and changes in the organism's environment.

Each tree and its environment is an individualistic system that is self-organizing. Self-organization results from negative feedback loops functioning to maintain essential variables within the limits for life. However, the properites of the old and new environment may be used with operational measurements to help explain why the trees behaved as they did (Evans 1976). Numerous examples of unexpected behavior of relocated trees are given by Dorman (1976) and Wright (1976). The experience is that behavior and responses of individualistic systems are not properties flowing independently of material happenings. Thus, tree rings may reflect past environment.

The operational definition of individualistic systems is the measurement used to identify the discontinuities. Systematists may use these measurements to place the individualistic system

in a species. Geneticists may use the measurements to place the individualistic system in an interbreeding population. These two types of classifications are based on the observed biological characteristics of continuity, irreversibility, and structure of the measured elements.

Individualistic systems are structured to be self-organizing. They do not respond in exactly the same way to the same environmental change every time the change is encountered. For example, people react differently to a sudden, loud noise if it is expected than if it is unexpected. Plants respond to a rapid decrease in temperature in relation to the preceding temperature regime. Organisms have parts connected to physical channels that transmit information in the form of energy and matter to direct the responses of the system in relation to the state of the system.

In contrast to self-organization, other systems are deterministic. For example, a watch responds repetitively to the same environmental change, such as winding and setting, every time the change occurs. The parts of the watch are connected to transmit information about time as recorded deterministically. Watches do not self-organize relative to uncertain environments. A watch cannot sense when it is keeping incorrect time and self-organize itself to make corrections. The watch system, therefore, is deterministic because the structure does not include decision mechanisms for self-organization; the watch cannot change the information flows across the wheels as the external environment changes.

Decision mechanisms in organisms include not only the central nervous system in higher animals but also the anatomic, physiological, and genetic mechanisms. Decision mechanisms are observed in both single (Koshland 1977) and multicelled organisms (Horridge 1977). The decision procedures

are mechanical or chemical. The evidence is that organisms are able to self-organize, to change behavior in relation to the goal for survival, to change information flows internally, and thus change states of organization in an uncertain environment. These decision mechanisms are explained by cybernetic concepts (Am. Soc. Cybern. 1972; Ashby 1973; Becht 1974; Forrester 1961; George 1977; Klir 1969; Kogan 1975; Milsum 1966; Wiener 1961) as discussed in chapter 2.

Decision mechanisms, sensors, and physical information carriers in organisms include membranes in single cells, chemical compounds, and physical structure. Effectors (fig. 7) include muscles, membranes, biochemical reactions, water movement, ion transfer, and cell movement.

The decision mechanism decides what is to follow in relation to a goal built into the organism by genetics, physiology, and anatomy. The overall goal (see fig. 7) built into all organisms is survival. Of course, this goal is composed of many different subgoals and feedback loops. Examples are the negative feedback loops that maintain levels of blood sugar, balance in animals, and openings and closings of stomata in plants. Organisms without the overall goal of survival do not live long enough to play significant roles in the structure of communities, in reproduction, and in evolution (Dobzhansky and others 1977; Simpson 1969; Stebbins 1974). Failure of only one of the essential feedback loops results in death. "Correct" decisions are those that change the state of the organism to maintain life. Decisions result in many kinds of action, such as movement from irritating substances, feeding, and a change in electropotential of a membrane. Most survival decisions are determined not by crises, such as escaping from a predator, but by goals to maintain essential variables, such as the amount of water in leaves, within the limits for life.

Decision and control between two closely arranged organisms both responding to approximately the same environment can now be examined (fig. 12). The environment directly affects the state of each organism and indirectly affects the kinds of decisions. Changes in environmental factors--light intensity, day length, ions around a plant root, and temperature--change the state of the organisms. When the information about the

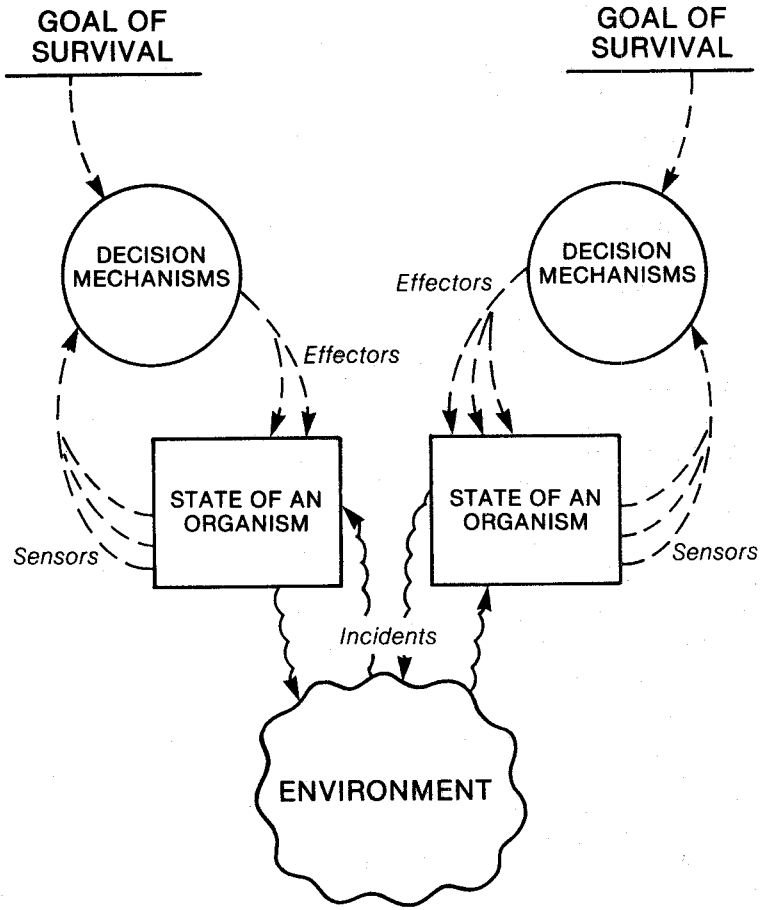

Figure 12.--Decision and control between two closely arranged organisms both responding to approximately the same environment. (The lines connecting the organism and the environment are wavy to indicate the unplanned effects between the two.)

state of the organism flows to the decision mechanism, another change usually occurs in the state of the organism. The organism changes itself in relation to the environment. Removing one's finger from a hot stove immediately rather than waiting until the state of the environment is changed from "hot" to "cool" is an example of how environment affects the organism's self-organization. The environment is not a part of the negative feedback loop, but the environment may change the behavior of the organism by indirectly affecting the kinds of decisions.

The environment is changed incidentally to the behavior of the organisms. We have no evidence that trees lose their leaves in order to maintain some amount of organic matter and nutrients in the soil. Stomata open and close in relation to the state of the plant and not to maintain some amount of water, oxygen, and carbon dioxide in the surrounding air. Conversely, the amounts of organic matter and nutrients in the soil are unplanned consequences of the states of organization. Bird nests, termite nests, and other structures built by organisms change the environment. This kind of dynamic change by organisms is self-organization; that is, a change is made in the chemical and physical state of the organism in relation to environmental changes to maintain essential variables within the limits of life.

Some components of environments such as heat, water, and oxygen seem to influence all organisms. Other elements in the environment affect only certain organisms. Whether or not the element is an environmental factor depends on the physical and chemical state of individual organisms. For example, colorblind people respond to wavelengths of light differently from normal-sighted people. Sharks and related animals respond to low-frequency, feeble, voltage gradients that are not detected by other organisms (Kalmijn 1977). Certain wavelengths and periods of radiation are

environmental factors for some organisms but not for others. Each organism and its special environment is different from every other organism and its special environment.

It is the individualistic system that self-organizes and dies or survives, contributes to community structure, and transmits genes to the next generation. Self-organization is for the present state of the organism. The physiological mechanisms are negative feedback loops and not feed-forward loops (see ch. 2). Self-organization is directed toward keeping essential variables within the limits for life now and not toward organizing for some optimum strategy (Lewontin 1979). When individualistic systems self-organize, their communities transform aimlessly. Without a structure that contains negative feedback loops to direct members toward a common goal, communities do not have a strategy to partition environmental resources, to maintain a certain community structure, to occupy a certain habitat, or to form a certain gene pool.

The individualistic systems that self-organize through all stages of development and in relation to all environmental changes are the ones most likely to transmit genes to succeeding generations. Those individuals that transmit genes to the next generation are "naturally selected"; by definition those individuals have the highest Darwinian fitness in the population. Natural selection is viewed as self-organization of individualistic systems directed by genetic and developmental processes.

A clear understanding of this definition of "natural selection" is important for directing the states of forest organization to provide desired human benefits. No external control mechanisms naturally select which organisms are to die and

which are to survive. Darwinian fitness (Dobzhansky and others 1977) and adaptability (Conrad 1979) result from self-organization of individualistic systems.

Because of self-organizing capabilities, the individualistic system functions in uncertain environments. Conrad's (1979) definition of adaptability is: The ability to function in the face of environmental uncertainty. This definition implies negative feedback loops that self-organize the system for the present environment and adjust the organism's structure as the environment changes.

Conrad's (1979) definition can be expressed mathematically. Communities of individualistic systems consist of ensembles of distinguishable states with the behavior of the former represented by a set of transition probabilities. These transition probabilities are recognized as stages of succession. Conrad (1979) expresses this mental model in mathematical symbols and demonstrates a simulation of environmental uncertainty. DYNAST is a modified system dynamics version of this mental model.

The concept of the individualistic system places the dynamics of all ecosystems on a physical basis. It requires that interchanges and interactions within ecosystems be physically described in terms of the structure for transfer of energy, information, and materials. For an ecosystem to exhibit goal-striving behavior, there must be physical information networks that include sensors, effectors, and decision mechanisms that function by comparing the stage of the ecosystem to a goal. Also, corrective actions must direct behavior of the ecosystem toward the goal.

> **The mortality of individualistic systems organizes survivors into communities without goals and with the dynamics of systems without negative feedback loops.**

Large numbers of seeds and other propagules, which are individualistic systems, die by their own dynamics. This mortality organizes the survivors into successive states.

These successive states have dynamics similar to those of the watch previously described. But biological communities have a major difference. Watch hands exactly repeat former states, whereas biological communities do not. If the genotypes and environments are similar to combinations in preceding forests, the kinds of states and individualistic systems will be similar but not identical to those of the preceding forest. The successive organizational states are irreversible and may appear to be repetitive. These apparently repetitive organizational states are known as stages of succession.

Forest communities are organizationally unstable because the surviving individualistic systems are joined without community goals directing negative feedback loops. In the absence of such feedback loops, the community cannot sense its own organizational state and cannot use past states to influence future actions to achieve a goal for the community. The community has no decision mechanisms to direct the life, death, reproduction, and replacement of individualistic systems to achieve a community goal. The forest community is an aggregation of survivors, and no species is essential for community organization because there is no common goal toward which all direct their behavior. For example, the loss of

the American chestnut (Castanea dentata (Marsh.) Borkh.) did not destroy eastern hardwood forests. The chestnut trees were replaced by other individualistic systems.

Successive generations of individualistic systems are genetically and environmentally different from preceding generations and will never again be exactly repeated. In the absence of community sensing and decision mechanisms, forests continue without goals.

This theory for community organization means that unmanaged forests never come to a steady state. In the words of Gaylord Simpson (1969), ". . . if indeed the earth's ecosystems are tending toward long-range stabilization or static equilibrium, 3.5 billion years has been too short a time to reach that condition."

During the 100-year life of dominant trees in a forest, millions of seeds and other propagules die. This organizing mechanism for communities is different from that of individualistic systems. Communities have no physical communication channels that link the individualistic systems to a decision mechanism. Therefore, the forest has no centralized decision mechanism that decides which species are to survive and which are to die. There is no goal for a certain association or for a certain distribution of species. Thus, there cannot be natural steady states, equilibria, or climax forests.

Individualistic systems in a community are linked only through the environment (fig. 12) and not through a communication network to a decision mechanism that coordinates behavior, survival, and mortality. Coordinated behavior results from similar genotypes responding to similar environments.

The theory for organization of forest communities states that order in natural communities results from the mortality of individualistic systems. Mortality occurs when the individualistic system fails to maintain some essential variable within the limits of life. The dynamics of this organizing mechanism for communities are similar to those of systems without negative feedback loops.

Aimless systems are operationally defined as those without information networks that link sensors, effectors, decision mechanisms, and goals. A watch is such an aimless system. Information, energy, and materials may flow through the system, and transformations from state to state may be predictable. However, no decision and control structure can be physically identified, measured, and related to a goal for the transformations.

Forest communities are aimless systems because no information networks have been structured for decision and control. Communities are aggregations of individualistic systems that we identify and measure in terms of the distribution of species. The structure of communities is defined by the morphologic, chemical, and genetic measures that are meaningful for our purposes. These measures describe the community in terms of human perceptions of actual experience; the simultaneity of communities is described relative to the operations for taking the measurements. It is the actual experiences of different people that make the concept of communities useful for forestry.

The terms "natural selection," "succession," and "competition," imply optimization, direction, purpose, decision, and control in the transformations of communities. Tansley (1935) presented evidence for rejecting the "organismal concept," which proposes self-organizing qualities for communities. The idea that ecosystem dynamics is an

ordered, directed process that leads to predetermined community process characteristics, such as stability, is an appealing human perception that is not supported by operational definitions.

Succession is sometimes described as an orderly process, reasonably directional, community controlled, and culminating in a stabilized ecosystem (Odum 1975). Both communities and organisms are given strategies. The succession strategy is increased control of the physical environment to achieve maximum protection from environmental perturbations. Another view interprets behavior of individuals as mechanisms that increase the representation of their genes in subsequent generations (Wilson 1975). The concept of strategy is defined as groupings of similar genetic characteristics that recur widely among species and cause them to exhibit similar behavior (Grime 1979). Medawar (1982) proposed that many people have a deep-seated sense of purpose of things, especially of natural communities. This sense of purpose, strategy, and stability in ecosystems seems to be supported by beliefs that an organism's behavior should contribute to the inheritance of progeny.

"Optimization" is the jargon for describing the organismal concept. Lewontin (1979) suggests that optimization is a convenient way to explain ecosystem dynamics in terms of problem solving and population strategy. Some arguments postulate that organisms, populations, or communities transfer genes to the next generation through evolved phenotypic mechanisms. These arguments explain evolution in terms of idealized properties, which are not described by operations performed in concrete situations to measure the actual happenings. In this approach, evolution is described as an aimless process in ecosystem dynamics (Dobzhansky and others 1977).

The aimless dynamics of the forest community result from the aggregate behavior of individualistic systems that, as populations, are aimlessly evolving. The phrases "natural selection," "succession," and "competition" describe measured changes in ecosystem dynamics.

Flows of Energy and Materials

> **The flows of energy, nutrients, carbon dioxide, water, and organic materials are unidirectional and have the dynamics of systems without goals and without negative feedback loops.**

The flows of energy and materials through the landscape are delayed by the individualistic systems that compose the forests. Flow rates are modified by changes in the states of community organization. Cycling is viewed as an additional delay ultimately determined by the dynamics of individuals.

The significance of this theory is that the delays in flows of energy and materials are brought to a steady state when the state of forest organization is brought to a steady state (see ch. 1). There are many such states and an equal number of flow combinations for energy and materials. Perhaps an inventory of the organizational states of the forest, such as that supplied by the model (see figs. 4, 5, 6), can eventually be used to indicate the delays in the energy and material flows. One application would be to estimate the nutrient flow into streams. This information could contribute to an index for biological productivity of streams.

This theory is supported by information from many sources. Consider, for example, the flow of radiant energy to the earth and its eventual dissipation to the universe (fig. 1). The forest

ecosystem traps small amounts of this energy and delays the rates of flows for varying amounts of time. Regardless of the delay periods and the hierarchy of organisms in the communication channel, the direction of flow is always in one direction--dissipation to the universe.

Cycles, such as the "nitrogen cycle," can be conceived for materials that are not dissipated to the universe. However, the flow of nitrogen through the forest ecosystem is always in one direction. The hierarchy of organisms through which nitrogen flows delays the flow relative to the self-organizing capabilities of the individualistic systems.

The delay and the dissipation of energy and materials by organisms is not easily explained by theories or equilibrium thermodynamics. The difficulty is well stated by Spanner (1964). In an epilog to his book he notes that life as we know it is always associated with the delay and the dissipation of matter and energy, the two entities with which the second law of thermodynamics is concerned at equilibrium conditions. Then he points out that every aspect of life turns on the existence of a lack of equilibrium; for instance, the ability to see presupposes nonequilibrium between the radiation the eye is emitting and the radiation it is receiving from the outside. He observed that if the universe is moving inevitably toward thermodynamic equilibrium, then as far as the biologist is concerned, all organisms will die.

Biological processes lead to evolution, migration, and extinction of life forms with no genetic and environmental stability (Dobzhansky and others 1977; Simpson 1969; Spurr and Barnes 1973). A new stand of trees is not usually the repetition of a preceding stand, although repetitive stands may be physically classified as seedlings, saplings, poletimber, mature timber,

and old growth. It is a remote probability that environments and species will be repetitive for two consecutive 100- to 300-year periods. The probability that newly established seedlings will have the same genotype distribution changes with mortality as the stands transform from seedling to old-growth states (Boyce and Cost 1978).

Phenomena that do not pass through successive equilibrium states are considered in studies of nonequilibrium thermodynamics. This area of investigation is also called the thermodynamics of irreversible processes (Wiśniewski and others 1976). Nonequilibrium phenomena are described by modern nonequilibrium thermodynamics. This section relies on the monographs by Glansdorff and Prigogine (1971) and Nicolis and Prigogine (1977) for most of the ideas applied to nonequilibrium forest states. For additional information, examine the works of Groot and Mazur (1962).

If the amount of living biomass comes to some steady state, the outputs of energy and materials equal the inputs (Vitousek and Reiners 1975). Natural mortality and tree harvest temporarily increase flow rates of water, nutrients, and energy. As stands succeed to the old-age organizational state, increased mortality rates cause increased energy and materials flow. Various forms of perturbation, such as storms, insects, diseases, fire, silviculture, and harvest, increase the mortality rates. The result is to speed the natural, aimless transformation of the forest through a series of successive new states (Smith 1977). But, the states are in nonequilibrium as are the flows of energy and materials.

If a small opening is formed in a forest by the death of a single, dominant tree, seedling growth may increase and new propagules may be established. However, an understory seedling or

sapling may not fill the space left by the tree that died; more often, surrounding trees grow until their crowns and roots fill the vacated space (Roach and Gingrich 1968). The forest has not returned to the previous state but has shifted to a new state.

The simultaneous death of contiguous, dominant trees creates large openings that may be filled by ingrowth from the understory. In this case, the sprouts and seedlings in the understory may begin to grow rapidly but eventually die. New propagules may be established but many of them die. Mortality accentuates the fluctuations in numbers of survivors. Survivors in large openings continue to grow, often at an increasing rate, and may fill the space vacated by the dominant trees that died. The result is the transformation of the stands from one organizational state to another. Species composition is transforming through nonequilibrium states; species composition and flows of energy and materials do not reverse.

Nonequilibrium conditions resulting from mortality lead to unidirectional energy and materials flows. The flows through the forest community are dissipative rather than conservative and are toward increased entrophy. The dynamics of these flows through the forest are without goals or negative feedback loops. Conservative flows occur in the negative feedback loops of the individualistic systems. For example, ions in many plants move from the leaves to the stems before the leaves fall. But this movement of ions within the plant is not determined by the plant behaving to achieve a goal for the forest. The negative feedback loops function within the plant to maintain certain variables, such as ion concentrations, within certain limits. We have no evidence that plants store and release ions to achieve an ion-concentration goal for the forest. Organisms

delay and dissipate but do not regulate flows of energy and materials to achieve a goal for the forest.

Some authors (Dobzhansky and others 1977; Simpson 1969) estimate that 99 percent of all species that ever existed are extinct. As organisms evolve, migrate, and become extinct, the coexistent species that form a state of forest organization change. Changes in both environments and in genotypes cause each succeeding forest stand to differ from the preceding one. Thus, the dynamics of forests may be readily understood and explained by the principles of nonequilibrium phenomena.

This bionomic theory for flows of energy and materials is simply a statement of observed phenomena that relates the behavior of organisms and communities to the thermodynamic principle of increasing entropy of the universe.

Multiple Benefits

The states of forest organization determine the kinds and proportions of multiple benefits available from a forest.

Many variables define the physical organization of a forest area: plant and animal species, age and size of the dominant plants, amount of shrubs and herbaceous plants, depth of the litter, volume of accumulated wood, amount and proportional distribution of nutrients, physical structure of the soil, biomass, and the flow of nutrients and water through the forest. Different combinations produce a large variety of habitats for plants and animals and a correspondingly large variety of potential human benefits including scenic values, hunting, hiking, timber, and streamflow. It is the proportional distribution of habitat type that provides a particular combination of benefits.

The significance of this theory is: changes in organizational states of a forest determine the particular combinations of sustained benefits produced. There are as many patterns of benefits as there are patterns of physical organization.

States of forest organization are operationally described in terms of stand type, size, and age class. We can recognize and measure stands of seedlings, saplings, poletimber, mature timber, and old growth by forest types. And we can measure the areas and the ages of the stands, which are dependent on the time and the size of openings formed by natural mortality and timber harvest. For convenience, we call these states habitats (Elton 1949).

Seedling stands provide a potential livelihood for plants and animals that do not occur in older stands. Old stands provide for the livelihood of plants and animals that do not exist in younger stands. Yet, some organisms exist in all states of forest organization. Furthermore, the area and the dispersion of stand types influence the quality of the habitats for plants and animals. For a given forest area, the distribution and the areas of seedling, sapling, pole, mature, and old-growth stands determine the potential for a livelihood of most endemic plants and animals.

Nonequilibrium environmental conditions appear conducive to a diversity of genotypes and to the continued natural evolution of the largest number of endemic species. A highly constrained and uniform environment limits the number of species, limits the range of variation for self-organization, and may speed the natural rates of extinction.

The multiple benefits theory describes natural rates of evolution, migration, and extinction in relation to the organization of

habitats. Each habitat combination provides particular human benefits, such as timber, water, or hunting opportunities.

Validation of the Bionomic Theories

One way to validate the bionomic theories is to put them to practical uses that will either confirm or deny them. In forestry, this method requires a large number of periodic observations. It is incorporated into the management system through monitoring, research, and inventories (fig. 3). Statistical methods and empirical research are used to evaluate relationships described by the theories. Thus, the value of the theories and the management structure is examined by day-to-day experience as well as by specialized scientific and technological methods. Constant iteration of the control loop (fig. 3) helps to apply technology, validate theories, and improve decisions.

The direct method for maintaining congruence of the mental models with the real forest requires relating the theories to changes in macroscopic phenomena such as plant and animal reproduction, growth, and mortality. Model predictions are compared with changes in the real forest. Following the comparison, the theories are accepted, rejected, or modified. The direct method is traditional for practically all methods of forest management.

This approach reduces the dynamics of forest ecosystems to a description of human perceptions of the actual happenings, gives the mental models the validity of actual experience by different people, and reduces mysticism in both the physical and mental models.

Hypothesis for Falsification of Theories

Another way theories are validated is to state a critical hypothesis that would falsify the theory if found to be true (Becht 1974; Popper 1959, 1962). Examples of such hypotheses are stated for each of the bionomic theories. Until a critical hypothesis is found to be true, the four theories are not falsified and can be used to construct forest management systems (fig. 3).

Individualistic Theory

The theory for individualistic systems would be falsified by discovery that any individualistic system's existence, mortality, or behavior is for the exclusive achievement of a goal for the forest community. Proof of this hypothesis requires evidence for a centralized, community decision mechanism and communication channels to control and direct the behavior of each individual to benefit the entire community.

Organization Theory

The theory for organization of forests would be falsified by discovery of a control and communication mechanism that senses the states of community organization, makes decisions, and directs the mortality and behavior of organisms to achieve organizational goals for the forest community. This critical hypothesis is the same as for falsification of the individualistic theory. This hypothesis, however, emphasizes an information network that senses the organizational state of the forest, whereas the preceding hypothesis emphasizes an information network that senses the behavior of individuals. Proof of both hypotheses depends on discovery of physical communication networks and decision mechanisms that direct the behavior of each individual to benefit the entire forest.

Flows Theory

The theory would be falsified by discovery of sensing and decision mechanisms in the community that regulate the inflows, internal status, and outflows of energy and materials to achieve organizational goals for the forest community. This hypothesis depends on the discovery of an information network that monitors the energy and materials flows and a decision mechanism that directs behavior of the individualistic systems to regulate the flows to achieve a goal.

Multiple Benefits Theory

The theory for multiple benefits would be falsified by discovery that all potential benefits are simultaneously available from a single state of community organization. This hypothesis requires proof that any single habitat could provide all potential benefits.

Chapter 4

Silvicultural Applications

Overview

Forests are cultured to provide from one to many benefits singly and in different combinations. Silviculture, based on scientific information and experience, is the use of cultural practices to enhance the benefits perceived to be in the self-interest of the interested parties. "Interested parties" includes all people who are interested in how a forest is cultured--from joint landowners, a landowner and a timber buyer, a management team for a forest industry, a forest supervisor and the staff, forest users, public forest managers, a board of directors, to a forestry consultant and a client. Benefits include commodity items used in commerce, such as timber, and noncommodity items not used in commerce, such as hiking and bird watching. The kinds of benefits expected may include wilderness experiences only, timber only, habitat for a single game animal, or any number of combinations.

Silviculture is the use of knowledge and technology to direct the behavior of the self-organizing, individualistic systems that make up a forest. The directing actions or cultural practices are designed to guide the ecosystem and order the forest to produce biologically possible and desired benefits.

In this chapter I examine some concepts of the silvicutural application of ecosystem dynamics.

Bionomic Theories That Underlie Silviculture

Forest ecosystems are enormously complex because large numbers of variables change

simultaneously. Yet because of self-organization of individualistic systems, only three control variables are required to systematically order ecosystem dynamics of forests--conversion of forest types, rates of timber harvest, and sizes of openings formed by harvesting. This orderly way to transform the forest from one state of organization to another creates predictable, time-changing states. The states are temporal and spatial dispersion of habitats that can be used to project the potential for any and all forest benefits, singly and in combination.

The theory of multiple benefits (see ch. 3) relates benefits to states of forest organization. The theory of organization of forest communities relates states of forest organization and stand structure to mortality. Mortality is related to self-organization of the individualistic systems theory. Controlling timber harvests, opening sizes, and conversions of types are effective ways to direct ecosystem dynamics and achieve desired states of forest organization. This approach is a modification of many silvicultural practices used for hundreds of years. The new approach is more responsive to social and economic changes and is simpler to use than past practices. It provides a way to plan the future availability of benefits singly and in different combinations, a way to integrate the knowledge of ecosystem dynamics and the technology for silviculture, and a way to project biologically possible combinations of benefits.

The uniqueness of the bionomic theories is that they are operational. The theories are stated in terms of control and communication mechanisms for organisms and communities of organisms. The theories describe cybernetic relations within and among organisms and provide the basis for logical silvicultural actions. Management decisions founded on this approach to silviculture convert the aimless dynamics of unmanaged forests to a goal-oriented management system.

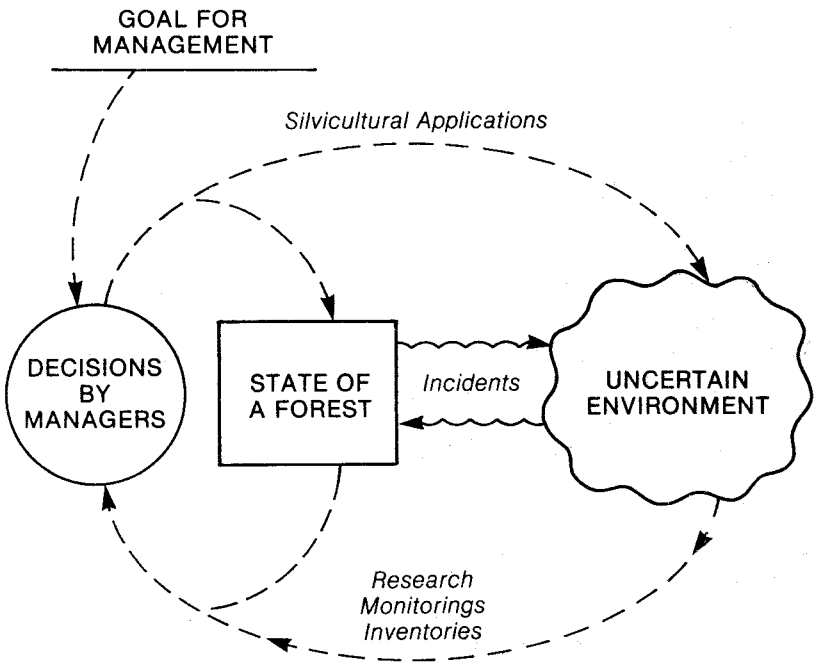

Figure 13.--How a state of forest organization is made a single goal for silvicultural applications (Boyce 1978b).

The management goal (fig. 13) is determined by consensus of all interested parties (see also fig. 3). The particular combination of benefits, those projected by the DYNAST model and chosen by the interested parties, determines the organizational state toward which the forest is to be moved. This particular state is the management goal for the next planning period, about 10 years. Once the interested parties reach a consensus, the control loop is activated (fig. 3). Then management of a specific forest becomes the responsibility of persons trained in the various forestry disciplines such as hydrology, wildlife biology, silviculture, soils, engineering, pathology, entomology, recreation, and landscape architecture. These specialists are included under the word "managers."

The control loop is a cybernetic system that functions for a planning period or until some unusual event, such as wildfire or storm, requires a new decision. Managers use their professional knowledge, experience, and insight to choose specific stands for harvest, to shape openings, to identify stand areas that do not exceed the range of opening sizes used in the selected DYNAST simulation, and to implement in-place enhancements. The harvest rates and opening sizes projected by DYNAST are parts of a dynamic plan that guide the decisions of managers to apply the silvicultural practices needed to bring the forest to a single goal, which is the desired organizational state.

Silvicultural applications modify both the state of the forest and the environment (fig. 13). Self-organization of the individualistic systems in relation to direct and indirect effects of silviculture contribute to changes in the forest's organizational state. Research, monitorings, and inventories inform managers how the forest is transforming. This information is used to adjust the silvicultural applications that keep the forest transforming toward the goal.

Steady-State and a Regulated Forest

A forest is in a steady-state whenever the distribution of stands by forest type, age, and area classes is constant. The forest is dynamic in that each age class transforms to an older class and the oldest class transforms to the youngest class. Such a condition is maintained by a constant timber harvest rate and an equally constant regeneration rate. As time approaches infinity, oscillations in the distribution of stands by age and area classes are insignificant. The steady-state condition does not occur in real forests because of differing harvest and regeneration rates and unplanned disturbances such as fire and insect attacks.

A typical silvicultural problem is to bring the distribution of age classes toward a desired steady-state. When at the steady-state, a forest is said to be regulated (Ford-Robertson 1971). Most forests deviate from the desired steady-state because of inadequate time under management, catastrophic events, land use changes, revised management objectives, or changes in social and economic forces. The steady-state is a goal for planning purposes. It is a goal toward which silvicultural actions are directed but one that is rarely achieved in a real forest (fig. 13).

Sustained Benefits

The quantity of timber that can be removed year after year from a forest is determined operationally by the distribution of stands by forest type, age, and area. An enormous number of possible stand distributions will provide a sustained, annual removal of a quantity of timber.

Achieving the sustained harvest goal is determined by success: (1) in bringing the stands to the required physical distribution of age classes and (2) in bringing about harvest and regeneration rates that maintain the age classes within acceptable limits of the required distribution. The latter condition is a steady-state distribution of age classes that is rarely achieved and difficult to maintain. In reality the age class distribution oscillates as management decisions respond to the effects of wildfire, insects, diseases, weather, and social and economic changes.

The value of the sustained benefits concept is to set a single goal for the next planning period toward which cultural actions are harmonized.

When the harvest rate is set, the physical distribution of stands by age classes is also set.

In order to have harvestable stands available for a sustained timber yield, a minimum amount of area must be kept in younger aged stands. This minimum distribution of age classes for annually harvesting a quantity of timber is determined biologically by the tree species, the soil productivity, the geographic area, the cultural practices, and the climate.

The minimum distribution of age classes required and the quantity of timber that can be removed annually determines the rate of transformation from the present state of forest organization toward the desired state. It is this "near future" transformation period that determines the availability of timber and other benefits. And it is this next decade of transformations, directed toward a distant goal, that is of special interest for choosing cultural actions and for determining the availability of benefits.

Transformations toward the steady-state determine not only the quantity of timber but also the quantities of all other forest benefits that can be enjoyed and continuously removed from a forest. The combinations of habitats for all plants and animals, changes in streamflow, movements of sediment and nutrients, and all other benefits including the quantity and kinds of timber are functions of the harvest and regeneration rates (area/year) and the sizes of openings (area) formed by harvest.

This relation is the common denominator for producing any desired combination of benefits. The state of organization is the objective identified in a land management plan. The objective is a goal, a realistic way, to plan for continued benefits. But the combination of benefits actually available in the near future is determined by the initial state and the transformations through which the forest must pass in the next few years to achieve the goal.

The choice of a management mode for the next planning period is influenced by the benefits expected in the distant future, the goal, and the benefits expected in the near future. The latter combinations of benefits, which may dominate the decision, are determined by the essential transformations from the present state (ch. 3). The explicit model must and should display these transformations and the associated benefits.

Selective Mortality

Mortality is the primary mechanism that brings about the transformation of genetic and ecological structure. Selective mortality is used in silviculture to direct orderly changes in the states of forest organization.

Stand dynamics is driven by mortality, which results primarily from the mechanisms of self-organization. Mortality may result from human plans, natural destructive forces, or the inability of the organisms to maintain some essential variable within the limits for life. Mortality not only influences the kinds and proportions of genes transmitted to the next generation but also organizes the stands and the forests.

The most effective cultural technique is to selectively change mortality rates of forest organisms. This practice modifies mortality associated with self-organization. Regulating wildlife harvest, timber harvest, stand thinning, removal of undesirable insects, and use of herbicides and fungicides are all examples of practices for selectively changing mortality rates. These cultural techniques speed the transformation from one stand structure to another, initiate the beginning of new stands, and change the species composition of stands. The operational significance of these relationships is that transformations can be ordered, future organizational states can be planned, and the future availability of benefits can be projected.

Many historical concepts of succession, the transformation of stands from state to state, were based on some preconceived state of stability toward which transformations in such things as species, biomass, soil development, energy efficiency, and diversity were inevitably moving the plant and animal communities. These hypotheses are considered improbable because we have no evidence for the existence of a community information network that links sensors, effectors, and a goal to a decision mechanism. The transformations that are measured by variables such as timber volumes, biomass, species diversity, energy efficiency, and soil development are quantitatively explained by the behavior of individualistic systems. Individualistic systems, self-organizing and dying in an uncertain environment, drive the transformations that we call succession. Silviculture can speed these transformation rates.

Once we interpret succession as a visible result of organic evolution (ch. 3), we can begin to explain observed transformations in terms of specific phenotypes self-organizing in response to uncertain environments. This is not totally new to forestry. Most silvicultural plans are based on projecting the performance of phenotypes, species, or improved genotypes in relation to harvesting, site preparation, fertilization, stand density, or some other variable. Connell and Slatyer (1977), for example, describe succession in terms of the behavior of individualistic systems--phenotypes develop and die in an undirected sequence of environmental changes. Their models are made operational by projecting succession in terms of species facilitation, tolerance, and inhibitive properties. These phenotypic characteristics are further subdivided into attributes useful for projecting transformations in relation to past observations (Cattelino and others 1979). This operational approach leads to useful projections of both single and multiple succession pathways.

Once a new stand is begun in either unmanaged or managed forests, differential mortality rates among the individualistic systems determine the transformation rates of the stand from one condition class to another. The differential mortality rates may result from planned silvicultural actions, self-organization that fails to maintain essential variables within the limits for life, and environmental uncertainities such as storms and droughts. Once observed for some historic period, many transformations can be predicted within limits of error acceptable for decision and control. Such predictions are based on the expected self-organization of individualistic systems in an uncertain environment; thus, the predictions are not deterministic. Periodic inventories and monitorings, possibly at 5- to 10-year intervals, are required to adjust the predictions in relation to the real transformations.

Selective mortality is the most useful and most effective silvicultural practice. Almost every silvicultural action involves selective mortality to favor or eliminate a phenotype. This changes the rates and the directions of natural transformations and changes competition and natural selection (ch. 3). The specific techniques include thinning stands, preparing planting sites, adding fertilizers, draining soils, killing certain insects and disease organisms, removing and killing animals, harvesting game animals, and harvesting timber.

Timber harvest is the cultural practice that most effectively and efficiently changes mortality rates and directs ecosystem dynamics.

Biological Potential

The biological potential is defined as the amount of one or more benefits that are expected as a result of certain cultural practices (Boyce 1975). The upper limits of the biological potential cannot be estimated accurately. Manipulating

genotypes and cultural practices has increased the biological potential for specific kinds of benefits such as timber, water, recreation, and wildlife habitat. Knowledge about photosynthesis rates, water availability, incoming radiation, nutrient supplies, and respiration rates tend to confirm our intuitive feeling that the biological potential has an upper limit. However, it is more important for the practical decision and control process to understand the biological potential in relation to investment and cultural practices than to attempt to establish a hypothetical upper limit.

In practice biological production of benefits is limited more often by the cost of investments for manipulating genetic mechanisms and cultural practices than by the biological constraints. Most silvicultural research and development is carried out with the expectation that findings, when applied, will produce a lower cost benefit, an improved benefit, a new benefit, or some economically favorable combination of benefits. Basic research directed toward increasing the biological potential in relation to cultural practices leads the way for research and development to enhance the economic effectiveness of silviculture. The result is an increase in the biological potential resulting from step-by-step improvement in the environment of the forest or an improvement in the plant and animal genotypes.

A primary concern in forestry is not to reduce the resources that determine biological potential. For example, when cultural practices increase soil erosion and nutrient losses, the biological potential may decline. The biological potential may be maintained by increased investments in mechanical actions, fertilizers, and water. For some resources such as genetic diversity of plants and animals, cultural practices are designed to create habitat diversity in hope of maintaining the potential livelihood of all or most endemic species.

The biological potential for the livelihood of endemic species, for increased diversity of life forms, and for various combinations of benefits can be increased or decreased by the rate of timber harvest.

Rate of Timber Harvest

The harvest rate of timber, fuelwood, and other biomass is the primary variable used to direct transformations from one organizational state of a forest to another. For example, a mature stand can be converted to a seedling stand by harvesting all the standing biomass; a pole stand can be converted from a 6-inch diameter class to an 8-inch diameter class by harvesting or deadening the smaller diameter trees; and individual trees can be selectively harvested to speed residual tree growth and stand transformation in the same direction it would have moved without harvesting. Harvesting cannot reverse natural transformation direction, which is driven by natural mortality, but it can be used to direct orderly changes in the forest's organizational state.

Natural mortality of individual trees, tree groups, or entire stands transforms stands to seedling and sapling states. Natural mortality is viewed as a nonrandom, disorganized, and uncontrolled harvest rate although the biomass is removed more slowly than with mechanical harvesting. Yet, because the flows of energy and materials are always in one direction through the ecosystem (third bionomic theory), the direction of transformation resulting from both natural and directed mortality is always in one direction and is irreversible (ch. 3).

Rate of harvest is best scheduled by using a form of area control; for example, the land area harvested per unit of time. If dispersed individual trees are harvested, the area is the sum of

the gaps or openings formed in the canopy. The land area harvested for thinnings may be estimated or indicated by the crown area or the basal area of the stems removed.

Areas expected to be harvested are easily projected for a few decades. These projections are used to indicate the stand distribution by forest type, age, and area classes. These projected organizational states determine the availability of benefits at each moment. Scheduling the harvest rates is the primary control variable for projecting the future availability of different combinations of benefits.

Rotation periods for a fixed area are a convenient way to express harvest rates. The rotation period is the approximate age when the stands of trees are scheduled for harvest. For a given forest the scheduled harvest rate is the total forest area divided by the rotation period.

Single Rotation Period

Conventionally, single rotation periods have been used in forestry to produce different forest types and different site classes. The concept was to plan the successive tree harvest from the same land at approximately the same age. The criterion for a single rotation period is to produce a maximum amount of timber for a given forest type and site class.

Consider a forest of one type and with a narrow range of site classes. From experience and research, 80 years is the harvest age known to provide the largest amount of a given kind of timber (fig. 14). That single rotation age at which all stands are harvested determines the future organizational state of the forest if the purpose is to produce a certain kind of timber. Mature stands older than 80 years, old-growth

stands, and natural removals would not be permitted. The forest is transformed toward a state of organization in which each age class occupies an area equal to the total area allocated to timber harvest divided by the rotation age.

The single rotation method produces a certain kind of timber in the shortest possible time. No consideration is given to bringing about a dispersion of age and area classes of stands for producing a desired combination of benefits. Each stand area is scheduled to flow through a single

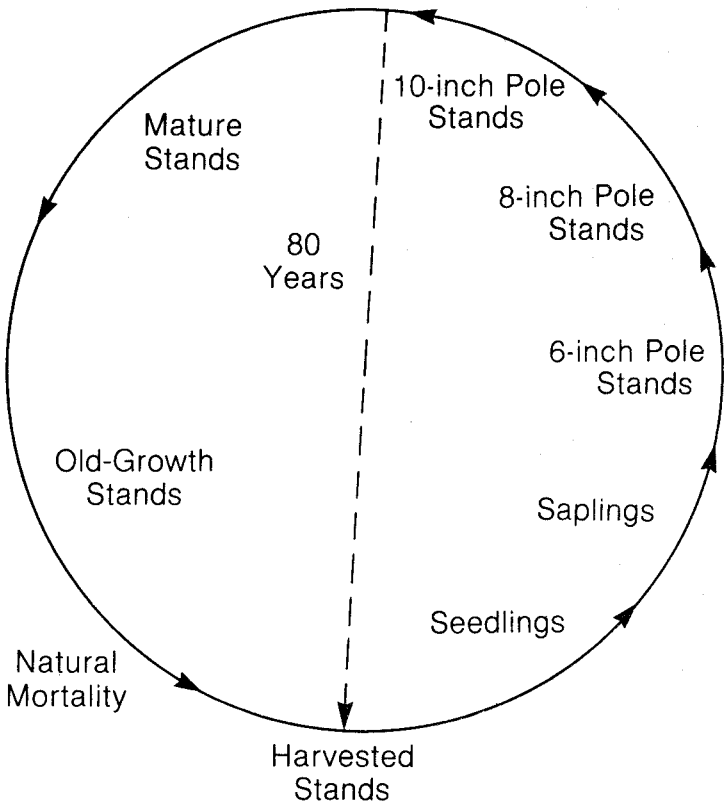

Figure 14.--A single rotation period is used when stands are harvested from the same land at approximately the same age. Diversity of habitats and benefits are limited to those provided by stands younger than the rotation age.

cycle of transformations such as from seedling stands to 10-inch pole stands and be harvested at the single rotation age.

The controls for a single rotation period are the single harvest age, the opening sizes, and the forest types formed by regeneration. The single rotation period can provide for a limited number of combined benefits (Boyce 1978a). The number and kind of benefits available are incident to the primary benefit, usually timber, that is the basis for choosing the rotation period.

Superimposed Rotation Periods

Superimposed rotations, also called dual rotations, are multiple rotation periods for the same piece of land. For example, a stand harvested at age 80 will pass through seedling, sapling, and other stages until it returns to the 80-year age class (fig. 15). At this time the stand may be harvested or permitted to transform to a 100- to 200-year-old stand. After the harvest of old-growth stands, the next harvest from the same area may be at 80 years or even younger. The rotation periods are superimposed on the same piece of land for succeeding generations. The stand ages at harvest may vary for each generation.

Superimposed rotations are the only way to create a diversity of age and area classes for any and all possible benefit combinations. Every biologically possible stand age and area can be scheduled, and combinations of benefits can be projected in relation to the transformation of the forest from the present to a future organizational state.

The controls are: the number of superimposed rotations, the harvest age for each rotation, the proportion of area cycling through each rotation, and the sizes of openings. For example, consider three rotations of 80, 100, and 200 years

(fig. 15). The harvest rate for these rotations can be changed by changing the proportion of area cycling through each rotation. When 80 percent of the area is cycled through 80 years, 10 percent through 100, and 10 percent through 200 years, most of the habitats will be in age classes less than 80 years. Changing the proportions of the forest cycling through the superimposed rotations, the size of areas harvested and the rotation periods permits an enormous number of different states of forest organization.

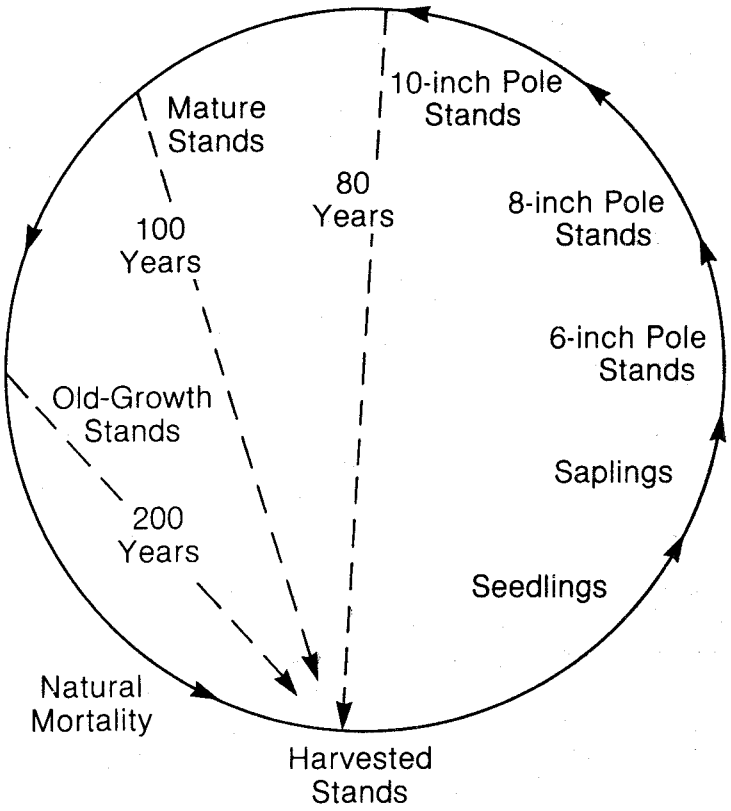

Figure 15.--Superimposed rotation periods are used when stands are cycled through different ages for harvest on the same piece of land. Diversity of habitats and benefits are not limited by stand age.

Typically two or three superimposed rotations are adequate to provide the desired combinations of stands by age and area classes. A large number of different benefit combinations are possible with superimposed rotations.

Size of Openings

Size of openings formed by harvesting is the second most important variable. The number of openings depends on harvest size and rate. Removing a single dominant or codominant tree creates an opening in the forest. In young stands, the opening made when a single tree is removed may not create a new age class as a permanent component of the stand. The surrounding trees may simply fill in the opening by increasing the growth of their crowns. When many contiguous trees are harvested, a new age class is formed. This new age class becomes a stand and is an important component of the organizational state. As opening size increases, the potential livelihood changes for different plants and animals. Although changes in opening size may be viewed as a continuum, different size classes are viewed as different habitat types. For example, habitats formed by removing a few contiguous trees are very different from those formed by removing several acres of trees.

Before the advent of forest management, openings were formed and shaped by wildfire, diseases, insects, weather, and human disturbances. These chance occurrences resulted in chance combinations of habitats and a widely fluctuating potential for many plants and animals. Planned cultural actions schedule tree removal to create opening sizes that maintain a dynamic dispersion of appropriate habitats for the potential livelihood of large numbers of plants and animals and for a desirable combination of human benefits.

In-Place Enhancements

Many cultural actions require decisions made in-place by a person trained in one of the forestry disciplines. These cultural actions are opportunistic in that they depend upon the state of the forest, the availability of investment funds, local markets, or demands for certain benefits. Some examples are thinning, pruning, leaving den trees, making water holes, locating trails, applying fertilizers, and weeding. Because such measures are planned by someone on the scene, they are termed "in-place." These actions cannot be easily predicted and are not incorporated into the planning model.

One important in-place decision for game animals is to schedule annual timber removals within the range of the animal's mobility. The dispersion of openings can be somewhat controlled by changing the harvest rates and opening sizes, but someone who knows the area's topography must review the specific sites with this principle in mind.

The results of any in-place enhancements should become readily apparent in the inventories of habitats and in the assessments of the algorithms. For example, if thinnings in pole stands speed the transition to mature-timber habitats, this change should be apparent in the inventories. It is not realistic to plan a thinning schedule far into the future in hopes of achieving some specific goal. Such plans can rarely be implemented because of changes in social and economic forces, technology, and benefit preferences. A better approach is to view those cultural actions other than harvest rates and opening sizes as opportunistic because in-place actions are taken to enhance benefits already made available by these.

Thinnings

Thinning is the process of making openings small enough to limit the formation of a new age class yet large enough to increase the diameter growth of the residual trees. Practically all research and controversies about thinning revolve around the size and number of openings needed to increase benefits and timber values. For example, the questions of whether to thin from below or above the average canopy level, how much basal area to leave, which species to keep, and when to thin are concerned with the monetary value of timber and the change in other benefits.

Thinning may change benefits other than timber. For example, if openings are large in thinned southern pine stands, understory hardwoods will increase their growth and provide more food and shelter for deer and other animals. These values may be provided in ways other than by thinning. For example, hardwood pole stands interspersed with pine stands could provide adequate feeding areas for some kinds of birds, and hardwood seedling habitats may provide browse for deer.

All of these enhancements depend on a large number of variables that are difficult to project. Thus, the rational approach to thinning for single or multiple values is to use DYNAST to simulate thinnings and to update the dynamic plan whenever monitorings and inventories indicate an enhancement in benefits.

Changes in Genotypes and Type Conversions

In some areas increased production of timber and other benefits can be achieved by changing genotypes and converting forest types. A type change can result from practices to favor different species or genetically developed genotypes. These practices depend on the manager's ability to control the kinds of genotypes that regenerate

after harvest, to increase the mortality of competing species, and to protect the desired genotypes from fire, insects, and diseases. Opportunities for making these kinds of investments typically occur on a small portion of natural forest land that has conditions suitable for culturing improved genotypes.

Forest types are changed primarily to enhance timber values, but type changes also may enhance other benefits. For example, by using silviculture to organize natural, intensively cultured, and other artificial stands by type, age, and area classes can increase the diversity of habitats and the potential livelihood for many plants and animals. Artificially establishing stands among natural stands is a way to maintain borders with distinctly contrasting age and type classes.

Natural Regeneration

Most of the world's forests result from natural regeneration, which is defined as stands originating from propagules formed by preceding stands and dispersed by natural events. Cultural practices can modify natural regeneration processes to favor desirable species. The most important cultural practice is to schedule the opening size formed by harvesting. This practice and the many associated modifications are often termed "silvicultural systems" or "regeneration systems."

The opening size formed by harvesting timber influences but does not control the species composition of the next stand. The opening size affects the potential livelihood of different species by changing mortality rates for the propagules. For example, opening size in coastal Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) forests influences soil surface temperatures, light, soil moisture, and frost (Williamson 1973). All of these variables influence the mortality rates for the propagules of Douglas-fir and all

other plants. The rates cannot be predicted within acceptable limits of error; thus, it is difficult to predict the species composition of future stands of Douglas-fir in relation to opening sizes. Some generalizations about expectations are useful when determined in-place.

In some forests the opening size may be chosen based on animal populations. For example, in the northern hardwoods the availability of browse for a given deer population influences the choice of the opening size (Marquis 1972).

The most obvious generalization from reports for each of 37 forests types is that scheduling opening size and harvest rates cannot assure a preconceived composition of natural regeneration (USDA FS 1983b). A second generalization is that harvested forest stands almost always naturally regenerate to another forest stand rather than to a grass or shrub stand. The regeneration delays and the species composition of the succeeding stands may be influenced by the opening sizes and the harvest rates. Additional practices such as disturbing the surface litter and soil during harvest, prescribed burning, disking, removing the slash after harvest, and direct seeding of desired species can contribute to achieving a desirable kind of successive stand, but these enhancements are not deterministic because individualistic systems are self-organizing.

It is likely that most of the world's forests will continue to be naturally regenerated for many decades. This situation coupled with the uncertainty of precisely predicting the species composition of naturally regenerated stands prohibits the use of dynamic plans dependent on predicting species composition for successive generations. For this reason the DYNAST planning model projects the distribution of stands by type, age, and area classes in relation to opening sizes and harvest rates.

If regeneration naturally or artificially changes species composition sufficiently to change the forest types, the model is appropriately adjusted. Monitorings and inventories at 5- to 10-year intervals are the sources of information for adjustments. Most of the conventional "regeneration systems" and silvicultural systems can be expressed in the DYNAST model by harvest rate, opening sizes, and delays. These simulations of change are not viewed as models of the "regeneration systems."

Relation of DYNAST Model to Regeneration Systems

The DYNAST model simulates the classical regeneration systems of silviculture (Assmann 1970; Davis 1954; Hiley 1954; Smith 1962; Troup 1952; USDA FS 1983b). DYNAST includes and perhaps supersedes these systems. It explores the consequences of manipulating the rotation period and opening size. Actually, the classical regeneration systems can be described by these two variables as modified by in-place enhancements. Properly considered, such apparently antithetical methods as "clearcutting" and "selection" appear as points on a continuum. Removing a selected large tree leaves a small opening in the forest; clearcutting a tract leaves a large one. Likewise, the "shelterwood" silvicultural system can be analyzed into harvest rates, opening size, and removal delays.

Other features by which the classical regeneration systems are classified seem to be based on erroneous assumptions. We speak of "high-forest" methods, which are supposed to produce stands grown from seed, and "coppice-forest" methods, which are supposed to produce stands from sprouts. But in the real forest, naturally regenerated stands contain trees originating from both seeds and sprouts. Sprouts can grow into tall, dominant trees. Likewise, we speak of "even-age" versus "uneven-age" management, but except for plantations, there are no even-aged stands.

The dynamically analytic silviculture technique enhances the classical systems. DYNAST is not limited by arbitrary categories but can examine thousands of possible combinations of rotation periods and opening sizes, assess the wider range of benefits produced under a multiple rotation system, and direct attention to the biologically possible combinations of sustained benefits that can be provided by harmonized management actions.

Selection Regeneration System

Mature and immature trees are selected and harvested singly and in groups to form openings of small and indeterminate size. The openings are small for "group selection" and often are arbitrarily limited to 5, 3, or 2 acres. In single-tree selection the openings are approximately equal to the crown area, which is related to basal area of the harvested tree. The harvest area is the entire forest or some area that includes the nonharvested trees. Harvest rates are controlled and measured by the timber volumes removed as related to the residual volumes, by a limit on the diameter of trees harvested, or by a formula, such as "Q values" (Wenger 1984), for removing trees from all diameter classes to bring the diameter distribution of an area to a preconceived standard.

The mental model presumes a forest structure in which every tree, except the largest and tallest, is a candidate to replace the next largest tree if it is removed. The dynamics of the real forest cannot function in this way because trees are rooted in place. They do not move to fill space vacated by harvesting; rather, each individualistic system self-organizes relative to whatever environmental changes are wrought by harvesting. There are no known information networks and decision mechanisms to structure diameter and age distributions for successively

replacing harvested trees. Expectations of successive replacement by ecosystem dynamics are difficult to fulfill when harvesting is controlled by volume, diameter limit, or a preconceived standard for diameter distribution.

The selection system favors understory trees, which usually have distorted stems and crowns, as the next dominants. These understory trees and the seedlings and sprouts that have survived in small openings are represented by a high proportion of tolerant species. These tolerant species, such as American beech (Fagus grandifolia Ehrh.), sugar maple (Acer saccharum Marsh.), and eastern hemlock (Tsuga canadensis (L.) Carr.), can self-organize to survive periods of low light intensity, low soil moisture, low nutrients, and allelopathic chemicals formed by plants or by organic decomposition. Some species, classed as intolerant to the conditions of closed canopy and small openings, may survive to become dominant trees.

Over several generations small openings will usually favor the tolerant trees, shrubs, and herbaceous plants. Note that it is not the method for controlling harvest rates but the opening size that influences the establishment, survival, growth, and eventually the kind and the shape of trees that occupy the overstory. Opening size is an effective variable for projecting, as in DYNAST, future states brought about by the selection system.

Group Selection Regeneration System

Group selection is applied to the selection system when openings are larger than whatever arbitrary limit is assigned to the "single-tree" selection definition. Typically, group-selection openings are less than 10 acres and may be as small as half an acre.

Because of the relatively small openings formed, these slection systems are often named "uneven-age management." The mental model is a forest brought to a state in which all annual age classes are represented in small stands. The smaller the stands, the more difficult it is to achieve the mental model in a real forest. In practice the selection systems represent the small-opening component of a continuum of regeneration systems. In DYNAST the selection systems are simulated as the small openings in a continuum of opening sizes.

Shelterwood Regeneration System

This system is characterized by timed removal of the overstory as a way to provide a few years of "shelter" for seedlings and sprouts. The overstory may be removed in two or more successive harvests at 1- to several-year intervals. The mental model is a stand of desirable species in which the rapid growth of seedlings and sprouts begins at about the same time. The term "even-aged" is applied to the new stand, although the root systems may be from 1 year to more than 10 years old.

The opening size after the last removal may be small but is usually larger than 5 acres. Harvest rate for the forest is controlled by the area and the number of openings. The opening sizes created by shelterwood systems overlap the larger openings formed by selection systems. DYNAST simulates the forest state by inserting opening sizes (area), harvesting delays (years), and harvest rates (acres/year) into the model.

Seed-Tree Regeneration System

This system involves leaving the minimum number of seed-producing trees that will result in a new stand. This method is used for intolerant species--those incapable of self-organizing when

under a canopy to survive periods of low light intensity, low soil moisture, and low nutrients. The mental model is similar to that for the shelterwood system.

Clearcut Regeneration System

This system identifies an area from which all trees larger than about 1 or 2 inches d.b.h. are removed or felled. The opening size is the area harvested. Harvest rate is controlled by the size and number of openings. The mental model of the new stand is essentially the same as for the seed-tree and the shelterwood systems.

The new stand originates from seed stored in the litter of the preceding stand, sprouts, seedlings established under the preceding stand, and seeds deposited on the area after harvesting. Intolerant and fast-growing seedlings and sprouts are usually favored. Tolerant species may survive under the faster growing intolerants and some of the tolerants may eventually become dominant trees.

Opening size may range from 1 to 100 acres or more. Classifying an opening by which regneration system was used is based on arbitrary definitions of the systems. The kinds, growth, and amounts of seedlings and sprouts after harvest are related to the opening sizes that form a continuum from the largest sizes formed by shelterwood and clear-cutting systems to the smallest openings formed by removing a single tree. The DYNAST model simulates the transformations of organizational states based on a continuum of opening sizes in conjunction with classical regeneration systems.

Both large and small openings may be scheduled to create a mosaic of stands by type, age, and area classes. Even the smallest openings formed by removing a single large tree typically

result in a new small stand. These small openings are often called "gaps," especially if formed by natural mortality. Differences in species composition and growth rates are continuums across the largest to the smallest openings. Criteria for measuring harvest openings can be based on the contiguous basal area removed, the contiguous crown area removed, or the contiguous land area exposed. Meaningful differences among the classes of openings are the correlations for species composition, growth rates, habitat potential for various plants and animals, and the timber harvesting cost. This operational definition is used in the DYNAST model.

Translating Information into Management Plans

Planning involves predicting the dynamics of a system in relation to actions. Assumptions about the future state of a system constrain both the number of variables and the rates and directions of change. The conventional variables of forest management are marketing, production, investment, and silviculture. Adding variables that describe the potential livelihood of individual game animals, nongame wildlife, endangered species, and recreation opportunities increases the complexity of decision making. The decision may not be "yes" or "no" for different amounts of present net value but could be a confusing combination of matrices and interaction coefficients.

The solution is to use simulation techniques that incorporate in-place decisions in the tactical processes and provide for all interested parties to use judgment as well as scientific data to make decisions. The judgment decisions are delayed until after the mathematical analyses are completed. This approach limits complexity in the communication of alternatives; aids the subjective use of insights; speeds the discarding of unacceptable alternatives; provides for periodic adjustment of decisions as social, economic, and

political forces change; permits the independent participation of all forestry diciplines; and maintains projected alternatives congruent with the real forest.

Complexity of Planning

Alston (1979) indicates the theoretical aspect of multiple use management is well-developed and simple to master. However, the practical applications by use of linear programming and matrices are overwhelming because of the complexity generated by attempts to match the benefits on a one-to-one basis with cultural practices and by attempts to develop interaction coefficients for the large number of variables. Alston uses a joint production model to illustrate the kind of complexity that limits decisions for producing different benefit combinations.

Dress and Field (1979) described the problem as a "multiple-criterion decision" that can be expressed in mathematical form as a notational extension of the standard linear programming approach. They recognize the difficulties of using linear programming to derive an optimal solution and to harmonize actions for multiple benefits. They describe the difficulties as follows: The set of solutions is made up of alternatives that are mixed in the sense that they are not based on comparable values in the linear programming process. This means that a mathematical decision must be made by somehow making the various objectives commensurate. The only way to do this is for the forest manager or for all interested parties to agree on a preference structure that mathematically orders solutions in the linear programming process. The complexity of ecosystem dynamics created by many variables changing simultaneously limits our ability to choose a preference structure before making the mathematical analyses.

Optimal analyses based on linear programming concepts are limited in management science by the tactical planning processes (Eilon 1980). What is desired is an integration of quantitative and subjective techniques to limit complexity and aid decision and control in the strategic management processes.

Constraint of Complexity

Complexity is constrained in the DYNAST approach by the subjective choice of a single goal, namely a forest's organizational state. The enormous variety of large numbers of benefits and cultural practices is absorbed by the equal variety of habitats that are dispersed spatially and temporally by the harvest rate and the opening size. Management actions do not attempt to match benefits on a one-to-one basis. Rather, they are used to direct the natural dynamics of the ecosystem to bring about desired organizational states.

One important constraint of complexity is to relate the availability of each benefit in a management unit to the distribution of various "habitats." A habitat is an area that possesses uniform physiography and stand conditions (Elton 1949), where plants and animals live (Odum 1971); some organisms require several habitats. The stages in a stand's development are habitats; a simple classification of them might include seedling, sapling, pole, mature timber, and old growth. Each such habitat is more favorable to certain species than to others (USDA FS 1979, USDI Fish and Wildlife Service 1982). The opening size formed by timber harvest determines the size of the habitat at all stages of the stand's development and also the quality of the habitat for certain plants and animals.

Timber harvest plays a dual role in the system. The timber removed is a benefit; the seedling habitat that follows is the beginning of

a sequence of new habitats. Because new stands transform at a predictable rate, the distribution and size of habitats at any time in the future can be estimated if the timber harvesting rate and the opening size are known.

Complexity is constrained. The availability of a combination of benefits, including timber, is determined by the distribution of stands by age, area, and type classes. The goal of silviculture is a desired distribution of habitats on the management unit.

Because habitats transform autonomously from state to state, only certain distributions can be maintained by silviculture. Ecosystems are never static. It is impossible, for example, to have only sapling and mature-timber habitats for a long period of time. The saplings eventually become poles and the mature timber may reach sufficient age to be considered old growth. Changes in the age for harvesting and the use of dual rotations coupled with control of the opening size provide many possible habitat combinations. For example, delays in harvesting mature timber increase the amounts of tree seeds, hard mast, and dens. Dual rotations provide fast rates of timber harvest from some areas, large trees for high-value timber from other areas, and habitats for many plants and animals that live in both old and young stands. The opening area determines the future stand area and thus influences the quality of the habitat for both plants and animals. The transformation rates in age and area classes are determined from biological knowledge. Thus, the displays of habitat distributions are those that are biologically possible.

Translation Process

What we want is to translate, in mathematical symbols, biological information into a new structure for forest management. The translation is to retain the original biological sense and limit the

complexity for using the information in decision and control. For example, the organizational state of a forest and the associated benefits can be expressed in mathematical terms.

Consider the time to be t and the time before it to be t-1. The difference is a small designated DT interval such as 1 day. A quantity of timber and other benefits, a, could accumulate in this interval and a quantity of timber and other benefits, r, could be removed or used in the same interval. Each increment or decrement is defined as an addition or subtraction to the cumulative quantity of timber and other benefits as stands flow through the number, n, of DT intervals, and thus through age classes. Without management and use there is still an increment and decrement (chs. 2, 3). For each quantity of increment there is a j age class and an i benefit and each addition must relate to a certain time interval DT. The whole range of possible accumulations is represented by $a_{ij}^{(t)}$. Similarly, removing a quantity of timber or other benefit is specified in the same way $r_{ij}^{(t-1)}$. The range in age class distribution is h_j for benefits including timber. The following expression describes the forest at a steady-state distribution of age classes. The accumulations equal removals for all benefits and are independent of time when DT is small.

$$\sum_{i,j}^{t} a_{ij}^{(t)} \, h_j^{(t)} = \sum_{i,j}^{(t-1)} r_{ij}^{(t-1)} \, h^{(t-1)}$$

The accumulation sign indicates the range for the system of equations represented by this expression for all possible benefits from the forest.

The definition of these equations is the subject of subsequent chapters. The unknowns to be

calculated are: (1) the transformations of the forest's organizational state from time to time, and (2) the benefits available at each state of transformation.

Biological information about the potential livelihood of plants and animals is translated into structures, such as yield tables, and then used in the simulation process. These kinds of translations provide information about differences in benefits and the potential livelihood of plants and animals. The future number of plants and animals, timber volumes, and present net values are projected for several decades. All of these variables are related as indices to changing states of forest organization in relation to silviculture.

The organizational state of the forest--the proportional distribution of stands by age, area, and type classes--and the transformations from various states determine the availability of benefits. The state of forest organization is the common denominator for translations and for decision and control.

Chapter 5

States of Forest Organization

Overview

A forest is viewed as a dispersion of stands that can be classified by age, area, and forest types. The stands transform from state to state naturally and as directed by silviculture. These transformations change the proportions of the stand classes and the way the stands are connected. For example, the transition areas between stands change as stands age. The dispersion of stands by type, age, and area classes defines the organizational state of a forest at a given time.

The state of organization is the common denominator for comparing the amounts of different benefits. It is the common connection among benefits. This connection can be defined in terms of the kinds and proportions of stands that provide more or less of one benefit in relation to another benefit. Benefits in DYNAST are not directly dependent on each other. The model requires no interaction coefficients among benefits. Benefits are projected independently of each other in relation to transformations in the organizational states of a forest.

This chapter describes how organization and structure are used in DYNAST to project benefits in relation to alternative management modes.

Organization and Structure Related to Benefits and Impacts

Structure is the way parts of a system are connected. The walls of a building are connected to form spaces for working, cooking, eating, playing, resting, and sleeping. The value of the benefits derived from a building are determined by

the arrangement, the interrelation, and the linkage of the walls, floors, doors, and windows. Different buildings provide different benefit combinations primarily because the different parts are structured in different ways.

The combination of benefits available from both buildings and forests are determined by structure. For example, the organizational state of different buildings can be expressed as the proportion of area in different room classes. A building's usefulness is related to the proportion and size of kitchens, bathrooms, etc. In contrast to the static structure of rooms in a house, stands in a forest are transforming spatially and temporally. Thus, a forest's organizational state, associated benefits, and impacts are dynamic.

From the bionomic theories (ch. 3) the availability of benefits depends on the physical organizational state of the forest--the proportions covered by seedlings, saplings, poletimber, mature timber, and old growth. Algorithms or mathematical statements of relationship are constructed to express how a particular benefit depends on the habitat distribution. The algorithms are written as linear or nonlinear relations. Each algorithm is independent of other algorithms and each algorithm may be added, deleted, or changed without affecting the core model or the other algorithms. People in different disciplines, such as hydrology, wildlife, and economics, can prepare algorithms that relate to organizational states without regard to algorithms prepared by others. The different benefits are related to each other by being related to the same organizational state.

The particular relations developed between habitats and benefits must always be regarded as tentative and subject to revision. Algorithms are derived from experience and scientific knowledge. Adjustments are made with new information.

For example, a potential timber index may be developed from existing yield tables. Monitoring the yields from harvested stands and new research provide information for making the algorithm more congruent with a specific forest. Monitoring and research in the control loop are important sources of information for improving the algorithms (fig. 3).

An important concern for the decision loop is to compare different benefits and impacts in relation to a common denominator (fig. 3). When all benefits of interest are commodities, then dollar values are established and money can be the common denominator for decisions. For commodities, the amount of each benefit multiplied by the market value establishes a basis for choosing the organizational state. If money is the basis for choice, the interested parties are expected to choose the DYNAST simulation that projects the largest net present value, highest realizable return rate, largest profitability index, or other measure of the monetary value.

However, many benefits are noncommodities--benefits are used or enjoyed without having an established dollar value. These kinds of benefits cannot be equated with the market price of lumber. Noncommodities may be priced in arbitrary ways such as estimating "money foregone"; estimating the cost for enjoying the benefit such as the money paid for binoculars, clothing, and travel; assigning the highest dollar values that interested parties will accept; and by finding out what some people think a noncommodity is worth. These kinds of evaluations are arbitrary and subject to disagreement among the interested parties. The dollar values assigned to the different benefits predetermine the choice of silviculture when the decision is controlled by the money values of the benefits (fig. 3). A lack of consensus occurs because the illusive values assigned to noncommodities cannot be proved by research and monitoring.

An approach based on what is biologically possible provides a way to compare amounts of benefits in relation to the costs for all benefits. The bases for decision are the optional benefit combinations that are biologically possible relative to aggregate costs. For this approach, each benefit--including monetary returns--is related to the organizational state of the forest. The DYNAST simulations display these amounts of benefits as indices ranging from 0 to 1. This kind of value function is computed by the appropriate algorithm.

One advantage to this approach is that algorithms are based on experience and research information. The mathematical relations are displayed as simple charts easily interpreted by people in different disciplines. And, each algorithm is directly dependent on an organizational state of the forest that can be defined, measured, and manipulated. Disagreements among interested parties can be assessed, but not necessarily resolved, by information from monitoring and research.

Another advantage is that all benefits, including cash flows, are operationally related to a common denominator. Benefits change due to transformations in organizational states and are only incident to changes in other benefits. The state of forest organization is the common denominator for both commodity and noncommodity benefits.

The next sections describe how information from research and experience is used to develop algorithms that relate amounts of benefits and impacts to states of forest organization.

An Algorithm for Timber

The purpose of the algorithm for timber yield index is to provide information for decisions and

for directing the use of control variables. Algorithms are not suitable for accurately predicting timber volumes (Avery and Burkhart 1983; Clutter and others 1983; Husch and others 1972). What is desired is a simulation of differences in the amounts of timber expected under different management modes. Yield tables based on age, site, and stand density are as useful for this purpose as any other prediction technique. A basic assumption for the timber yield algorithm is that errors associated with unexpected weather conditions, tree survival in regenerated stands, mortality rates, and changes in species composition will have approximately the same future effect for all management modes. This assumption is not always true because an old stand may be damaged by some agent more than or less than a young stand. Projections are useful primarily for assessing alternative management modes.

Once a new stand is initiated in either unmanaged or managed forests, relative rates of mortality among the species present determine the transformation rate of the stand from one condition class to another. Because of the similarity of genetic codes from generation to generation, the transformation rates can be projected within acceptable limits of error.

For example, a yield table for timber relates an expected amount of timber to a future organizational state--the area and age class of stands. The yield table is used to estimate changes in timber volumes when states of forest organization change. Yield tables and their use are described in numerous publications (Avery and Burkhart 1983; Clutter and others 1983; Husch and others 1972). A timber yield index illustrates how algorithms for timber can be developed.

For example, growth culminates at 50 years of age on all sites for mixed hardwood stands in the Big Ivy area near Barnardsville, NC (Schnur 1937). Age 50, therefore, is used as a reference age.

The index is referenced also to 100 percent stocking and to an average site index of 70. Yields for different management modes are computed and compared with the yield of 100 percent stocked, 50-year-old stands on areas with a site index of 70. Of course, other ages, stocking, and site indices could be used as a reference point for maximum timber production.

The reference yield selected is 2,680 cubic feet for all trees 0.6 inch d.b.h. and larger, excluding bark, age 50, density class 100, site index 70 (Schnur 1937, Table 34). This 2,680 is divided into the values for all ages, density 100, and site index 70. This procedure produces index values, called volume factors, that are plotted over age (fig. 16).

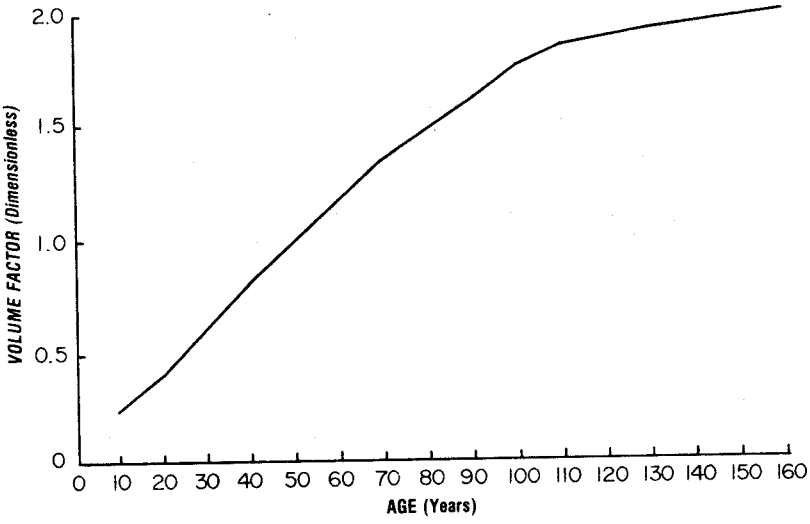

Figure 16.--Volume factors extrapolated to 160 years for site index class 70, density class 100 (Schnur 1937, Table 34).

At 50 years of age the volume factor is 1. As stands age, both the yield and the index increase but at a decreasing rate. We do not have enough information to accurately predict increments beyond 100 years. Thus, the yield index is extended at a conservative rate to 160 years.

Site index variations are related to timber yields. The reference value, 2,680, is divided into values for site indices 40 to 80, for age 50 and density 100 (Schnur 1937, Table 34). The results are plotted as a site index factor over site index (fig. 17). Few areas on the Big Ivy area have a site index of 90. The curve for site index factor is extended to 1.4 although no research data are available to support this value.

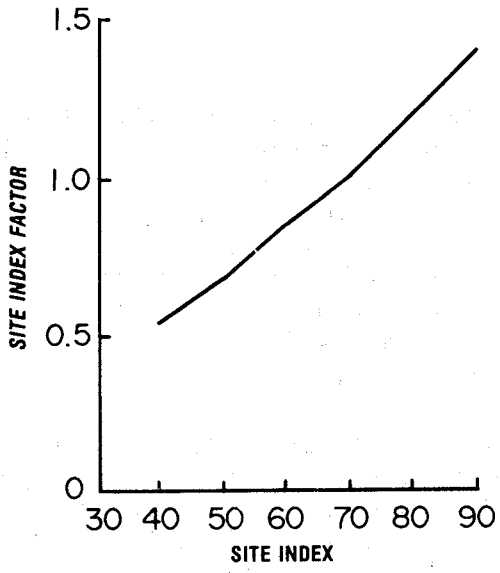

Figure 17.--Site index factors plotted over site index classes for site index 70 and density class 100 as the base (Schnur 1937, Table 34).

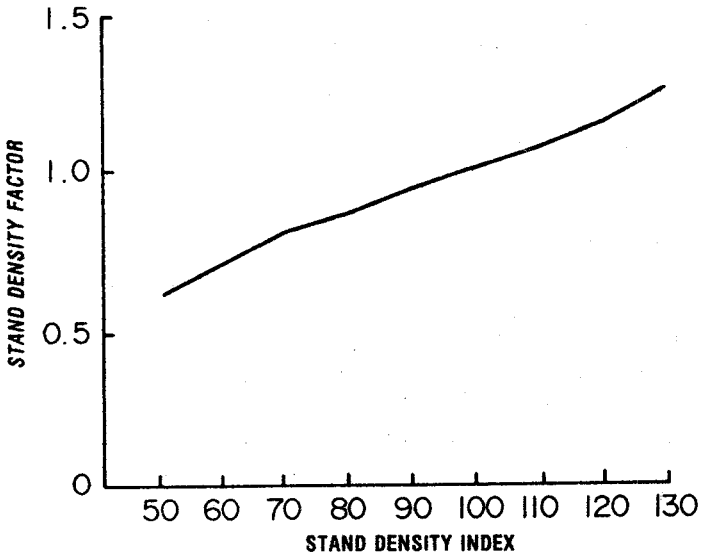

Figure 18.--Stand density factors plotted over stand density index referenced to site index 70 and density class 100 (Schnur 1937, Table 34).

Stand density variations are related to timber yields. The reference value, 2,680, is divided into values for stand densities 50 to 130, for age 50, site index 70 (Schnur 1937, Table 34). The results are plotted as a stand density factor over stand density (fig. 18). Most stands in the Big Ivy area are in the 90 to 100 density classes although some thinned stands may have a density class between 70 and 90.

If we know the age, site index, and density of a stand, the timber volume can be estimated by interpolating the factors from the appropriate curves and multiplying the factors by the reference volume, 2,680. For example, the volume estimated by this method for a stand age 80, site index 60, and stand density 90 is about 3,000 cubic feet (1.47 x 0.81 x 0.94 x 2,680). Schnur's table value is 3,045. Differences between the

interpolated and the table values are due to rounding and because the tables are only approximately harmonic.

The interpolated values are usually within 5 percent of the table values and are well within acceptable limits of error. An error of 20 percent is acceptable because of the uncertain future environment. It is likely that the real error for projecting volumes into the future is as high as 40 percent of the volumes in the yield table (Schnur 1937, Table 34).

The advantage of translating the yield tables into the indices is that these relations can be used in the continual simulation compiler DYNAMO (Pugh 1983). Values are interpolated between points on the charts. The reference volume, 2,680, can be changed to a different value without changing the indices because the tables are approximately harmonic. The indices can be easily changed to make them congruent with a specific forest. Most important, a potential timber index can be derived and related to the simulated organizational states of the forest.

Potential Timber Index (PTI)

The potential timber index is the ratio of the timber volume projected for harvest by the DYNAST simulation and the volume that would be expected for maximum, sustained timber production. The equation is:

$$PTI_t = VT_{t/TIM}$$

where:

PTI = potential timber index (dimensionless)

VT = timber removed from all habitats (cubic volume)

TIM = timber maximum for sustained annual harvest (cubic volume)

t = time

The projected timber volumes, VT, are derived from the DYNAST simulation and are determined by harvest rates used in the management modes being considered. The general equation for each habitat harvested is:

$$VTH_t = RML_t * YST * VF * SIF * SDF_t$$

where:

VTH = volume of timber removed from a habitat (cubic volume)

RML = area of habitat harvested (area)

YST = yield standard being used, i.e. 2,680 (cubic volume)

VF = volume factor, (fig. 16) (dimensionless)

SIF = site index factor (fig. 17) (dimensionless)

SDF = stand density factor (fig. 18) (dimensionless)

t = time

The timber volume expected for maximum, sustained timber production, TIM, is determined by the forest type area and harvest rate. The harvest rate, measured by the rotation period, determines the yield standard, YST. For example, if the goal is to produce the largest, sustained cubic volume and site index averages 70 and stand density averages 100, 50 years is the rotation period and the yield standard is 2,680 cubic feet.

The general equation for TIM is:

$$TIM = (TAH/TMR)*YST*VF*SIF*SDF$$

where:

TIM = timber maximum (cubic volume)

TAH = total area of habitats for a forest type (area)

TMR = timber rotation for kind of timber desired (years)

YST = yield standard being used (cubic volume)

VF = volume factor (fig. 16) (dimensionless)

SIF = site index factor (fig. 17) (dimensionless)

SDF = standard density factor (fig. 18) (dimensionless)

If small saw logs are desired, the timber rotation, TMR, is changed to 80 years. The yield standard then becomes 3,950 cubic feet for average site index 70 and average stand density index 100 (Schnur 1937, Table 34).

It is very difficult to predict which stands will be harvested (see ch. 4). The dynamic plan projects areas for annual harvest from each habitat, but in-place decisions are made to choose stands for harvest in relation to the social, economic, and environmental situations. For planning purposes values can be randomly assigned to harvested stands for the site index and stand density factors. Such stochastic approximations are not expected to coincide with the real values. For example, the randomly chosen site index factor

could be above the mean value for the forest, whereas the value for the real forest harvested could be below the mean value. For most decision and control purposes, assigning average values for future timber yields in relation to age, site, and stand density is much more useful than attempts to use stochastic variation. The end results will be the same for both methods and less costly simulations are made when stochastic approximations are omitted.

Meaningfulness of PTI

When the amount of timber projected to be removed is equal to the volume expected for maximum, sustained timber production, the PTI has a value of 1. When a DYNAST simulation presents a PTI value of 1 as the system approaches steady state, this particular management mode provides the maximum, sustained timber production. When the PTI exceeds 1, generally at the beginning of a simulation, this usually means that large volumes of timber accumulated before time zero. A PTI greater than 1 may occur when the initial inventory contains a large area of old growth; the controls can be changed to limit the harvest rate if desired.

As forest organization approaches steady state for a simulation, the PTI values should stabilize at a value between 0 and 1, depending on the management mode. Because PTI and indices for other benefits are based on organizational states and not on each other, the indices can be used to compare the availability of benefit combinations in relation to alternative management modes.

Limiting Complexity

A primary difficulty in decision and control is the complexity of ecosystem dynamics created by many variables changing simultaneously. This complexity in simulation models is impossible to

copy and predict. What is desired is a simulation of the differences in structural features of the ecosystem in relation to silviculture. The PTI should be responsive to alternative management modes with minimum complexity in the algorithm and the displays.

The displays are simple charts and tables that provide values for PTI and the projected timber volumes. The algorithm is complicated by including the site index and stand density factors. These factors can be omitted without changing the meaningfulness of the PTI values.

The yield tables are based on plots taken from a large area from Missouri to Maryland and from Tennessee to Michigan (Schnur 1937). Ninety-five percent of the plots are clustered in three site classes that range in site index from 50 to 80 (fig. 19). Stands would be harvested from all of the sites. A single stand of 20 acres may range in site class from 60 to 80. In a single year several stands with different average sites may be harvested. It is likely that the average site index for the forest is more realistic for estimating volumes for planning purposes than for projecting site index for harvested areas. Eliminating the stochastic variable for site index classes reduces complexity in the algorithm and does not alter the differences in PTI. The variable SIF is removed from the general equation.

Stand density transforms naturally toward the 100 percent class. Increased mortality rates typically keep most stands below the 100 percent class. Some young stands may exceed the 100 percent class for 10 to 20 years, but eventually mortality structures the stands near the 100 percent class. In most forests stand density fluctuations in an uncertain environment are difficult to project for individual stands.

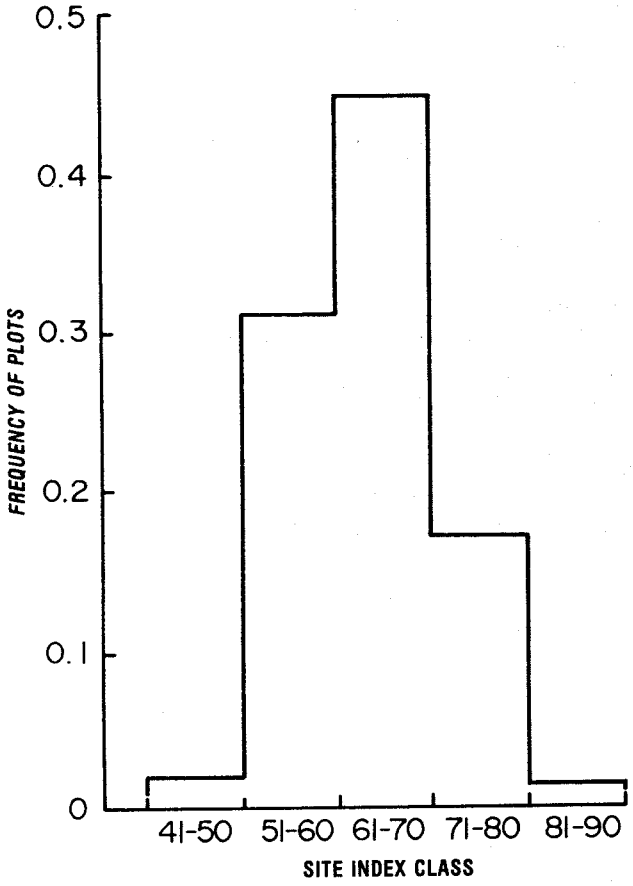

Figure 19.--The frequency of plots for five site classes for the yield tables (Schnur 1937).

Monitoring and periodic inventories, however, provide information about average stand densities for the stands being harvested. The variable SDF is omitted from the algorithm. Average stand density is included in the calculations by changing the value of the yield standard, YST. The yield standard is 2680 for a forest with average stocking in the 100 percent class, site index 70, and timber maximum rotation of 50 years. If this forest is consistently thinned to keep the average

stand density near the 70 percent class, the yield standard would be 2135 (Schnur 1937, Table 34).

The yield standard, YST, can be used to reduce complexity in the PTI algorithm. The yield standard selected for a particular forest is determined by the (1) rotation period, TMR, for the kind of timber desired, (2) the average site index for the specific forest being simulated, and (3) the average density of stands being harvested. Additional "fine tuning" of the model to the forest results from using information from monitorings, research, and inventories to change the yield table.

Small Openings Affect the PTI

The potential timber index is reduced whenever the average opening size is less than 3 acres. This reduction in PTI compensates for reduced seedling growth; for injuries to residual, border trees; and for the higher costs for harvesting small areas.

Timber harvest from small openings injures the crowns, roots, and trunks of surrounding trees. The losses may not be apparent at harvest, but in time the total yield is reduced (Biltonen and others 1976; Nyland and others 1976).

It is difficult to remove a large tree without creating an opening of at least 0.2 acre. The natural felling of trees in old-growth stands forms openings of this size (Williamson 1973).

Growth is slow for seedlings, sprouts, and residual trees in small openings (Marks 1974; Roach and Gingrich 1968; Trimble 1970, 1973). Growth is also retarded near the border of an opening. As the opening size decreases, the ratio of area to perimeter decreases. In a 3-acre, circular opening, there are 100 square feet of area for each foot of perimeter. In a

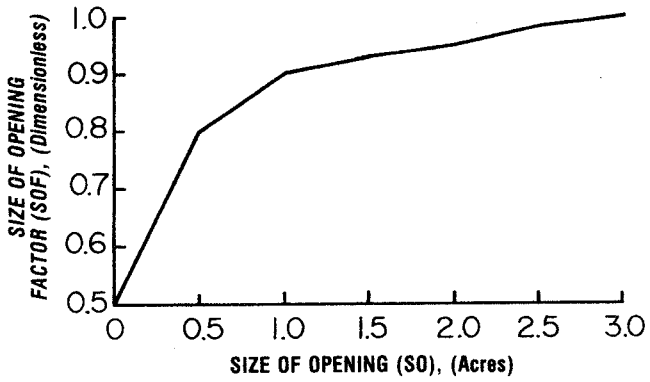

Figure 20.--The small-opening factor, SOF, adjusts timber volumes for losses when opening size is less than 3 acres.

0.5-acre opening, the area per perimeter foot is only 40 square feet. The limitation on growing space caused by this border effect is insignificant for openings larger than 3 acres, but it rapidly becomes more important for smaller openings. In the timber algorithm, the size of opening factor (SOF) adjusts for losses on a curve that approximates the decreases in perimeter when opening size declines (fig. 20).

The SOF factor is used as a multiplier in the equation for computing the timber volume removed, VTH. The opening-size factor has a value of 1 for opening sizes of 3 acres and larger. For these larger openings the timber volumes are not adjusted by the opening-size factor. For openings less than 3 acres the opening-size factor reduces the estimated volumes relative to the ratio of area to perimeter.

Timber volume losses associated with openings less than 3 acres are only partially measured at harvest time. The largest losses are in the adjacent stands. The injuries increase in size due to growth of wood-decaying micro-organisms and stain formation. The algorithm could include these delays, but they would probably not affect the decision and control process.

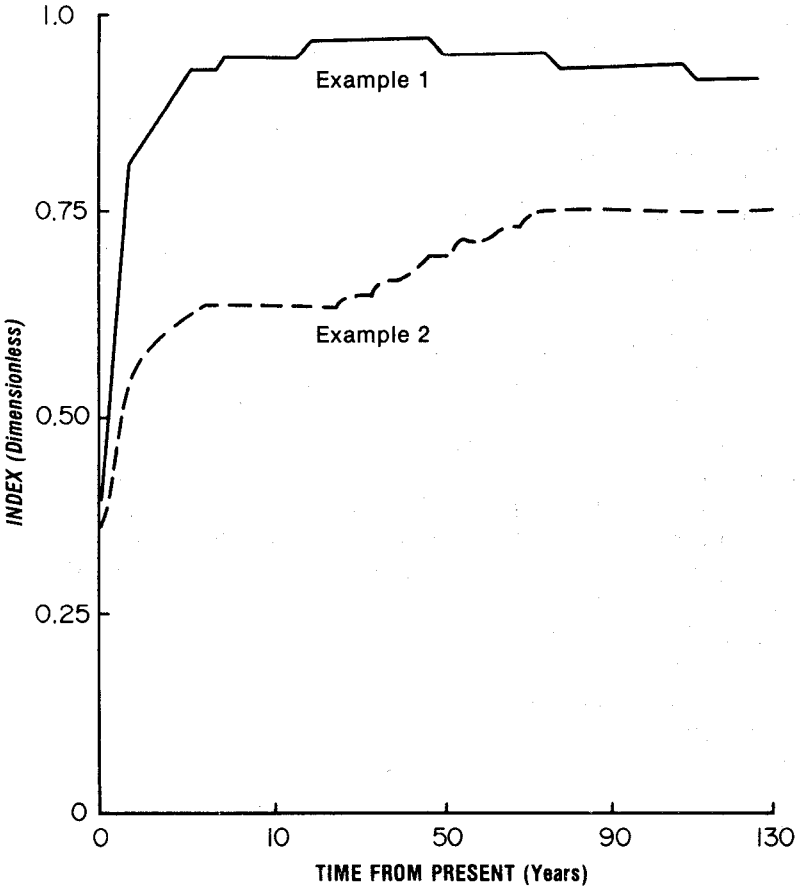

Figure 21.--Potential timber indices projected from time zero for two silvicultural modes. (Chart is copied from a plot made by the DYNAMO compiler.)

PTI Projections

PTI is simple to calculate. Values can be computed by using appropriate values from the diagrams (figs. 16, 17, 18). Calculating the PTI values by hand is laborious when projected for many years and when several different harvest rates are considered. A computer can speed the calculations.

Two examples of PTI projections are illustrated (fig. 21). The DYNAST model is used; the

displays are modified from those typically produced by the DYNAMO compiler (Pugh 1983).

The first example for projecting PTI envisions a silvicultural mode to harvest the old-growth stands and eventually harvest timber only from mature stands at 80 years of age. The timber volume removed approaches the maximum yield before time 50 years and then declines to a potential timber index of about 0.9 of the maximum yield that would be obtained at a rotation period of 50 years. The reason for the high index between time 5 and 50 is that the old-growth stands have higher volumes per acre than the 80-year-old, mature-timber stands. The old-growth stands are harvested during the first 50 years at a rate that will rapidly bring the forest to the desired organizational state. After 50 years the sale of old-growth timber declines. At time 130 years, the harvest is from 80-year-old, mature-timber stands. The PTI is about 90 percent of the timber volumes that could be obtained by harvesting when the mean annual increment culminates, age 50, and the forest is at a steady state. After about 130 years the index approaches steady state at about 0.9.

The next example for projecting PTI envisions the organizational state of a forest to maintain about 25 percent of the area in old-growth stands and to harvest timber from old-growth stands at age 300 and from mature-timber stands at age 90. For the first 30 years timber sales are made only from mature-timber stands. During this period the potential timber index increases to 0.6 of the maximum. From time 30 to 75, sales of old-growth stands are increased. The total volumes removed increase and the potential timber index is maintained at about 0.7 of the volumes that could be obtained if the rotation period were 50 years.

The timber volumes expected for the 10-year planning period are much greater for the first

than for the second example (table 1). In the second example more large-diameter trees are harvested after time 30. The lower volumes harvested during the first decade in the second alternative are the result of old-growth stands being accumulated. These old-growth stands may be desired for some reason as a part of the future organizational state of the forest.

What is important is not the predicted volumes but the differences in the volumes. These differences are the bases for decisions. The calculations and displays for timber alone would

Table 1.--Volumes of timber expected to be harvested during the first 10 years for two alternative management modes

Years from inventory	First alternative	Second alternative
	Thousands of cubic feet[a]	
1	198	151
2	263	173
3	276	187
4	286	194
5	294	199
6	299	202
7	302	203
8	305	204
9	306	205
10	307	205
Total	2,836	1,923

[a]Cubic feet to a 4-inch top for fully stocked stands, site index 70 (Schnur 1937).

likely result in decisions equivalent to those derived from other analytic methods. What is unique about the dynamic analytic method is that any benefit that can be quantitatively related to organizational states can be plotted and directly compared with other benefits, including timber.

Calculations of indices for benefits other than timber are based on the same principles as those used to project timber volumes. Data originate from research and monitoring. The data are translated into a usable format, such as a yield table. For wildlife habitats the format could be a habitat evaluation table. Comparisons are based on using a common denominator--the forest's organizational state--and displaying differences on a common scale from 0 to 1. The next sections examine this translation process for selected variables.

Water Yield Algorithm

Predictions of water yield in relation to future states of forest organization have uncertainties similar to those for predicting any future event. However, information from experimental watersheds can be used to project differences in streamflow expected for different organizational states. These projections are not expected to be precise for a specific future year because unpredictable variables such as rainfall and radiant energy reception due to variations in cloud cover affect the estimates. What we are concerned with is making a choice between alternative management modes in relation to differences in streamflow and differences in other benefits.

Experience and research leads to the mental model that watersheds with maximum forest cover, which have high potentials for evaporation and transpiration, have minimum water yields relative to precipitation. Maximum water yield is expected

from a completely sealed watershed with a smooth, unwettable surface. Between these extremes occur the real water yield rates for forested land. Timber harvests, measured as acres harvested per year and the opening sizes formed, can increase water yields above those from dense, undisturbed forest. And it is unlikely that severe treatments, such as converting a forest to a sealed watershed, are practical for large areas devoted to water yield.

What is desired is an algorithm that relates water yield to biologically possible and desirable organizational states of a forest. The information presented by Douglass and Swank (1975) is translated into a water yield algorithm for the Big Ivy area. The maximum sustained increase in amount of water measured at the Coweeta Experimental Watersheds near Franklin, NC, is about 8.5 acre-inches per year for annual recutting on one watershed and about 5.8 acre-inches per year for conversion of a forest to a low-vigor grass cover on another watershed. These flows are examples of an increase in maximum continuing water yields that could be expected from annually cutting regrowth. Smaller increases in sustained yields are expected from south- and west-facing watersheds. For the Big Ivy area the maximum sustainable increase in water yield by annually cutting regrowth is estimated to be about 5 acre-inches (0.417 acre-feet/year).

An algorithm for water yield increase is developed with an index ranging from 0 to 1. The index is the ratio of the projected increase in water yield for a given silvicultural mode to the maximum sustainable increased water yield, which is estimated to be 0.417 acre-feet.

The rate of streamflow increase for a silvicultural mode is related to the insolation index, which varies with slope steepness and aspect of the Big Ivy area. This value is used in the

Douglass and Swank (1975) equation to estimate the annual yield in inches of water. The first-year increase is estimated by the equation:

$$Q = a(B/I)^X$$

where:

Q = increase in water yield (acre-inches)

a = constant with the value 0.00224

x = constant with the value 1.4462

B = proportion of basal area removed by harvesting (percent)

I = insolation index with the value 0.27 for the Big Ivy area

Water yield for a given stand area increases during the first growing season after timber is harvested. The increase in water yield over that of undisturbed stands declines to approximately

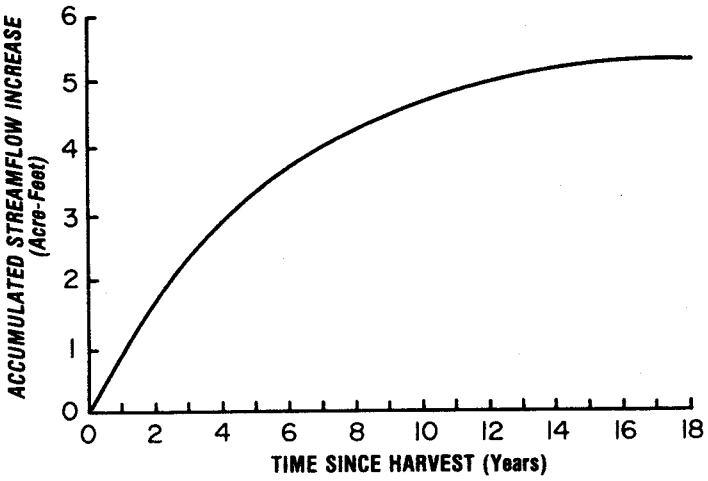

Figure 22.--Accumulated increases in streamflows estimated for the Big Ivy forest, by time since harvest of 100 percent of the basal area of a stand; average slope is about 14 percent and faces west.

Table 2.--Increases in streamflow expected on the Big Ivy forest, North Carolina, after harvest of 100 percent of the basal area

Years since harvest	Annual	Accumulated
	- - - - Acre-feet - - - -	
1	0.980	0.98
2	0.745	1.72
3	0.607	2.33
4	0.510	2.84
5	0.434	3.28
6	0.372	3.65
7	0.320	3.97
8	0.275	4.24
9	0.235	4.48
10	0.199	4.68
11	0.167	4.84
12	0.137	4.98
13	0.110	5.09
14	0.085	5.18
15	0.062	5.24
16	0.040	5.28
17	0.019	5.30
18	0	5.30

zero about 18 years after harvest (table 2). For a stand area in Big Ivy, if we plot the accumulated increase per acre in water yield for 100 percent basal area removed by years since harvest, we have a relation that can be translated into an algorithm in relation to the forest's organizational state (fig. 22).

No information is available about how opening size affects water yield. The algorithm is based

on the assumption that all opening sizes contribute equally to water yield and that the area harvested is the sum of the opening areas formed. The change in yield follows the curve for a B-value of 100 percent (fig. 23). The equations are:

$$WYI = WY / (Typ1 \times MSWI)$$

$$WY = (SEWI \times A1) + (SAWI \times B1)$$

$$SEWI = SEW/DA1$$

$$SAWI = (SAWM - SEW)/DB1$$

where:

WYI = water yield index (dimensionless)

WY = annual increase in water yield from entire forest type (acre-feet/year)

Typ1 = the forest area of Type 1 (acres)

MSWI = maximum sustainable increased water yield (acre-feet/year); this constant for the Big Ivy area is 0.417

SEWI = water from seedling habitats (acre-feet/year)

A1 = area of seedling habitats (acres)

SAWI = water from sapling habitats (acre-feet/year)

B1= area of sapling habitats (acres)

SEW = water increase for seedling habitats, read from the chart (fig. 22) (acre-feet/year)

DA1 = delay for seedling habitats (years)

SAWM = maximum accumulated increase for harvested areas, read from the chart (fig. 22) for age 18 years (acre-feet/year).

DB1 = delay for sapling habitats (years)

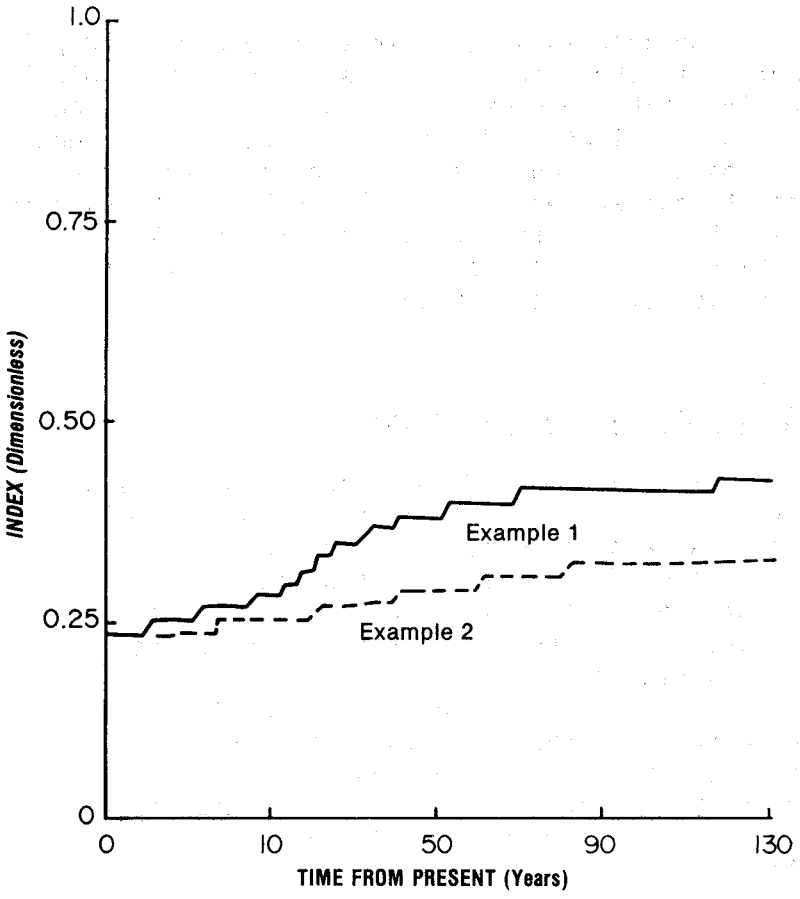

Figure 23.--Water yield indices projected from time zero for two silvicultural modes. (Chart is copied from a plot made by the DYNAMO compiler.)

Over time, monitoring and research data can fit the algorithm more closely to the forest's behavior.

The water yield index is simple to calculate and can be done quickly by using the DYNAST model to project organizational states and to relate the water yield index to these states. Two examples are illustrated. The organizational states are those used to illustrate the potential timber index (fig. 21).

The increases in water yield are related primarily to the increased areas in seedling habitat as the timber harvest rates increase. Both the potential timber index and the water yield index are based on transformations in the forest's organizational states. Timber harvests may be used to direct the transformations, but the transformations and the indices change in relation to the dynamics of the ecosystem.

Sediment Movement Algorithm

Particles of sediment flow through the landscape at varying rates, which are affected by slope steepness, wind, water movement above and below ground, and geologic substrate. Forests retard sediment flows. The flow rates of both organic and inorganic particles are delayed by the matrix of roots and soil and by the protective litter cover. Trees can be removed from forests with small increases in the sediment flow if the surface layers of litter and root matrix are not destroyed. Roadbuilding breaks up the litter cover and root matrix and increases sediment flows.

A practical index of sediment flow can be based on the number of openings formed per square mile of forest per year. The number of openings

is related to the number of miles of roads and skid trails required to remove the timber (Nyland and others 1976). As the size of openings decreases, the number of openings for equal harvest areas increases. However, when many small openings are formed, such as when single trees are removed, the miles of roads and skid trials required per opening may be reduced by clustering the openings. Thus, the relation between the openings per square mile and the silt production is not a straight line; sediment flow increases at a declining rate as the number of openings increases.

The sediment index has two components: a sediment increase based on the number of openings per square mile per year and a sediment decrease based on average opening size whenever the size is less than 3 acres. The sediment decreases whenever opening sizes are less than 3 acres because small openings are clustered to reduce the total miles of road and skid trails.

The rate of sediment decline for opening sizes less than 3 acres is determined by a table function (fig. 24). As the average opening size approaches zero, the amount of roading required for clustering the skid trails is assumed to be one-third of that for 3-acre openings. When the openings are larger than 3 acres, the amount of sediment is not reduced because it is difficult to reduce the amount of roading for these opening sizes.

The most important relation for sediment production is the number of openings created per square mile of forest per year. As this number increases, the miles of roads and skid trails that increase sediment movement must increase (fig. 25). An 80-year rotation at steady state requires a harvest of one 8-acre opening per year per square mile if harvest is restricted to a square-mile area and opening sizes are limited to

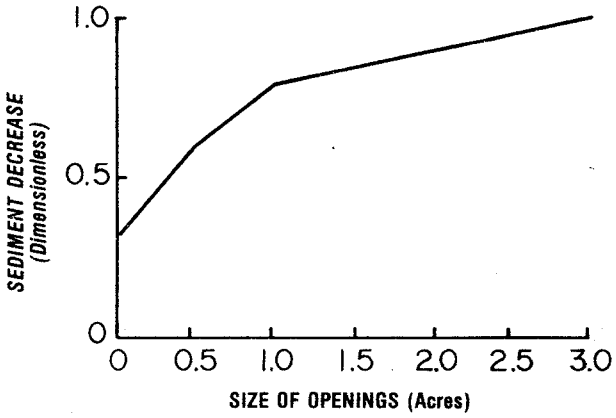

Figure 24.--Sediment decrease as a function of clustering openings less than 3 acres.

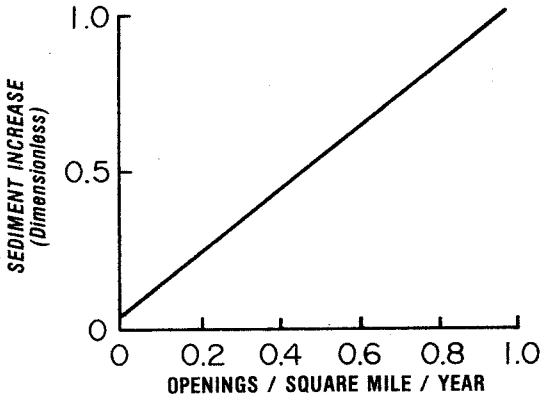

Figure 25.--Sediment increase resulting from increased road and skid trail construction as the number of openings per square mile per year increases.

8 acres. This is the maximum dispersion of openings for most management modes on the Big Ivy. Thus, the chart relates one opening per square mile per year to the maximum amount of sediment from road construction. The more typical case would be opening sizes of 25 to 30 acres with less

than one opening per square mile. Large openings greatly limit road construction and sediment flow.

The organizational states used to illustrate the potential timber index are used to illustrate the sediment flow index. In the first example, 25-acre openings with a random variation are used because it is not possible to make all openings exactly 25 acres. The random variation is based on a standard error of 2 acres; most openings are expected to be 25 ± (2 x 2.4) acres. In the second example, 10-acre openings with a standard error of 1 acre are used; most openings are expected to be 10 ± (1 x 2.4) acres. The smallest openings are larger than 3 acres, so the sediment decrease factor is not used.

By projecting the harvest rates for each example, we can project the number of openings formed per square mile per year. A random number table can be used to vary the opening sizes appropriate for the assigned standard errors. The DYNAST model is used to compute and plot the sediment indices for the two examples (fig. 26). Example 2 has the higher sediment flow although less timber is harvested than for Example 1. Example 1 has openings about 2.5 times larger than those for Example 2. Although more timber is harvested for Example 1, fewer roads and skid trails are required to connect the 25-acre openings than the 10-acre openings in the second example. The differences in sediment flows between Examples 1 and 2 are determined both by the harvest rates and the opening sizes.

Harvest rates and sizes of openings determine states of forest organization and are related to amount of road construction, which is related to sediment flows. A high sediment flow rate, relative to undisturbed forests, is an undesirable impact. The objective is to limit the sediment flow index to less than 1, which is the maximum acceptable limit. At an index of 1, one opening

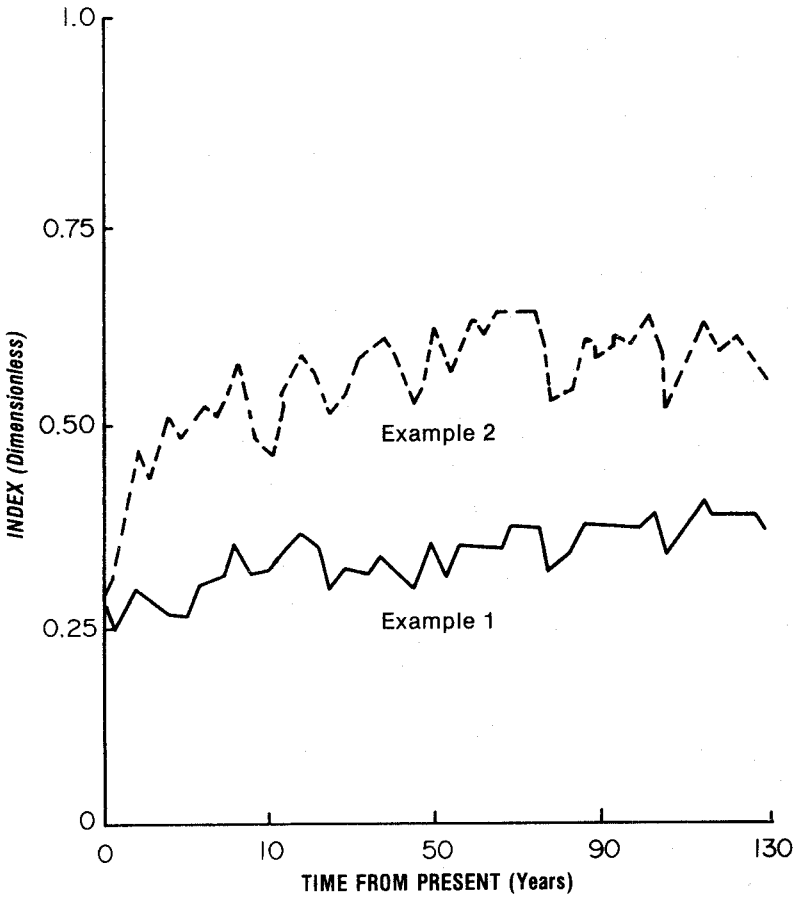

Figure 26.--Sediment flow indices projected from time zero for two silvicultural modes. (Chart is copied from a plot made by the DYNAMO compiler.)

is formed per year for each 640 acres of forest. In most forest situations more sediment is moved by constructing access roads to an opening than by harvesting the opening. For a given harvest rate (acres/year), sediment flow can best be reduced by the opening size, thereby reducing the miles of access roads and trails.

Habitat Algorithm for a Game Species

The white-tailed deer uses many habitats in the Southern Appalachian Mountains. The habitat

for this animal can be enhanced by bringing about an appropriate distribution of seedling, sapling, and mast-producing stands. Seedling habitats provide browse, soft mast, and minimum cover. Sapling habitats provide escape cover and bedding areas. If harvest rates maintain seedling habitats adequate for browse, adequate sapling habitats will be available. The 10-inch pole, mature timber, and old-growth habitats provide hard mast and cover.

Opening size is important for browse in the seedling stage, for cover and bedding in the sapling stage, and for the frequency of ecotone areas. About 1- to 6-acre openings provide large amounts of browse and a high frequency of mixed vegetation. Openings larger than about 1 acre provide escape and bedding areas. Openings that are 50 acres or more limit the utilization of browse in the seedling stage. Mature timber provides hard mast and cover.

The effect of opening size on deer habitat can be expressed by using one chart for opening size (Boyce 1977) and one for frequency in relation to harvest rate. Another way is to relate the deer habitat index to the number of openings per square mile (fig. 27).

The assumption is that one opening formed per year per 1,280 acres, 2 square miles, provides the sizes and the frequencies, both spatially and temporally, for maximum use of soft mast and browse by deer in the Big Ivy area. As the number of openings formed per year per square mile declines, the use of browse declines; this number declines as opening size increases and as timber harvest rates decline. Deer index due to openings does not go to zero when no openings are formed. In old growth and undisturbed forest some browse is available.

The total amount of soft mast and browse is related to the proportion of the forest in seedling habitat (fig. 28). When no seedling habitat

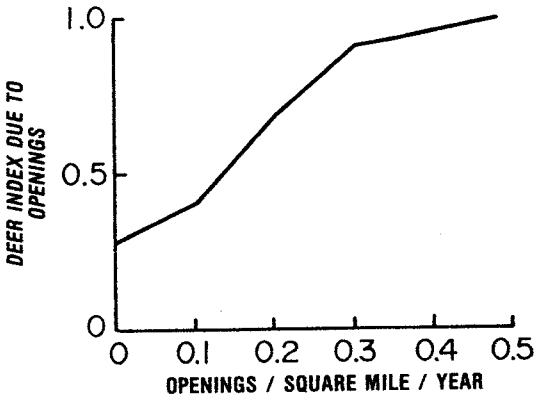

Figure 27.--Index of soft mast and browse potential for deer as a function of the number of openings formed per square mile per year.

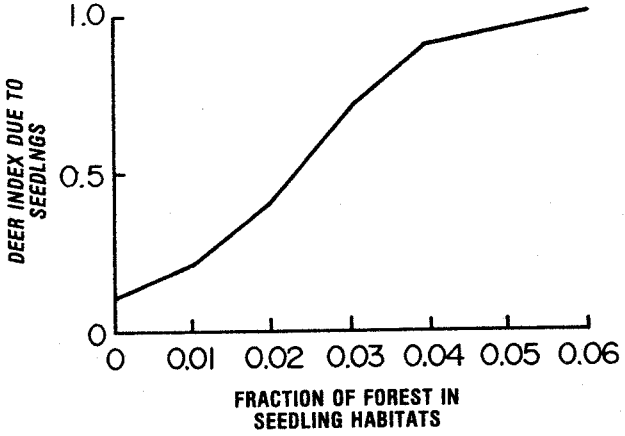

Figure 28.--Index of soft mast and browse potential for deer as a function of the proportion of area in seedling habitats.

is available, the amount of browse and soft mast is about 0.1 of the maximum. As the proportion of the forest in seedling habitat increases, the contribution of this habitat to the deer index also increases. The maximum amount of seedling habitat that could be acceptable for the Big Ivy area is about 5 to 6 percent of the forest. At steady

state, 6 percent of the area in seedling habitat 1 to 5 years old requires a rotation period of 83 years; for this rotation period, the deer index for seedlings is set at 1. Shorter rotations to increase the amount of browse and soft mast would not improve conditions for deer in the Big Ivy.

In different forests the relation between the deer browse index and seedlings may have a different shape from that illustrated in figure 28. From research monitoring and experience, different amounts of seedling habitats may be found to provide maximum browse. For example, the index may be found to have a value of 1 when 4 percent of the area is in seedling habitat. However, the direction of the relation is not likely to change. An increase in amount of seedling habitat from zero will increase the amount of deer browse up to a limit. With no information one could draw a straight line from 0.1 for zero seedlings to 1 for 4 percent of the area in seedlings. Even this limited assumption is useful for the decision and control process. Detailed research and monitoring would not change this relation but would provide evidence for modifying the shape and the limit of the relation.

First estimates for algorithms can be produced from experience and library sources. But new information is often needed to adjust the shape and the limit of the relationship to make the indices more congruent with a particular forest.

Hard mast may not be essential for deer in some forests, but an increase enhances the habitat for deer in many areas. When no habitats produce hard mast, the deer index is about 0.1 for the Big Ivy (fig. 29). When more than 70 percent of the forest is hard mast habitat, increasing the proportion does not improve the livelihood for deer.

The habitats producing hard mast are the areas in 10-inch pole, mature timber, and old growth. Old-growth habitats, especially some species of oaks (USDA FS 1980), produce less hard mast per unit of forest than the younger age

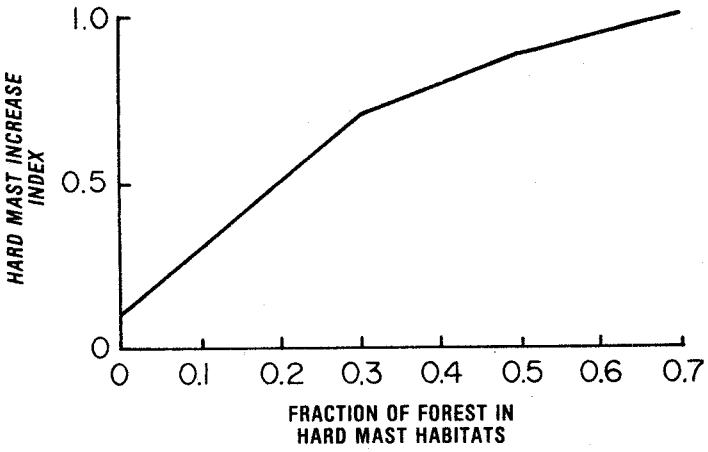

Figure 29.--Increase in availability of hard mast with an increase in the proportion of forest area in hard mast-producing habitats.

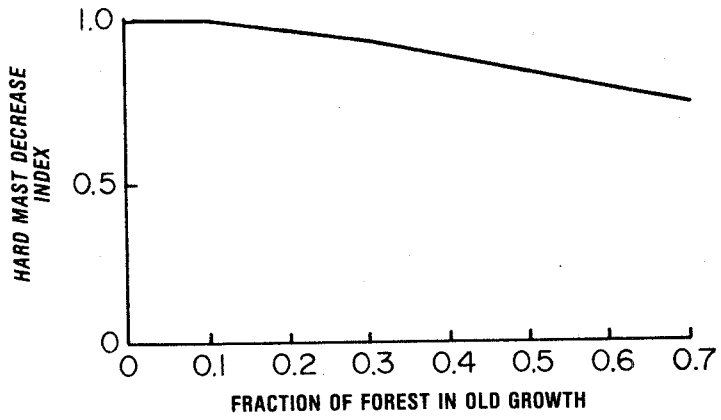

Figure 30.--Decrease in hard mast production as a portion of the stand advances into the old-growth age class.

classes. When the proportion of hard mast habitat consists of more than 10 percent old growth, the hard mast production index is decreased (fig. 30). The decrease is not rapid and is 75 percent of the maximum potential when all of the hard mast habitat is old growth. The hard mast production index may be used to estimate the potential livelihood for other animals such as squirrels and turkeys.

Because the indices are all on the scale of 0 to 1, values for the three relations can be reduced to a single number by multiplication. The deer habitat index is mathematically expressed:

$$DEER = HTD \times OTD \times HM$$

where:

DEER = deer habitat index

HTD = deer habitat due to seedlings (fig. 28)

OTD = deer habitat due to opening size and frequency (fig. 27)

HM = hard mast production index (figs. 29, 30)

Information for the calculations may be derived from the projection of the forest's organizational states. Projections are plotted (fig. 31) for the deer habitat index for the two examples previously described.

For the first decade, possibly a planning period, the deer habitat index is approximately the same for both examples (fig. 31). After time 10 the habitat index for deer continues to increase for Example 2 but declines for Example 1. After 50 years the index for Example 1 is still twice the initial value at time zero. For Example 2, the index is about three times the initial

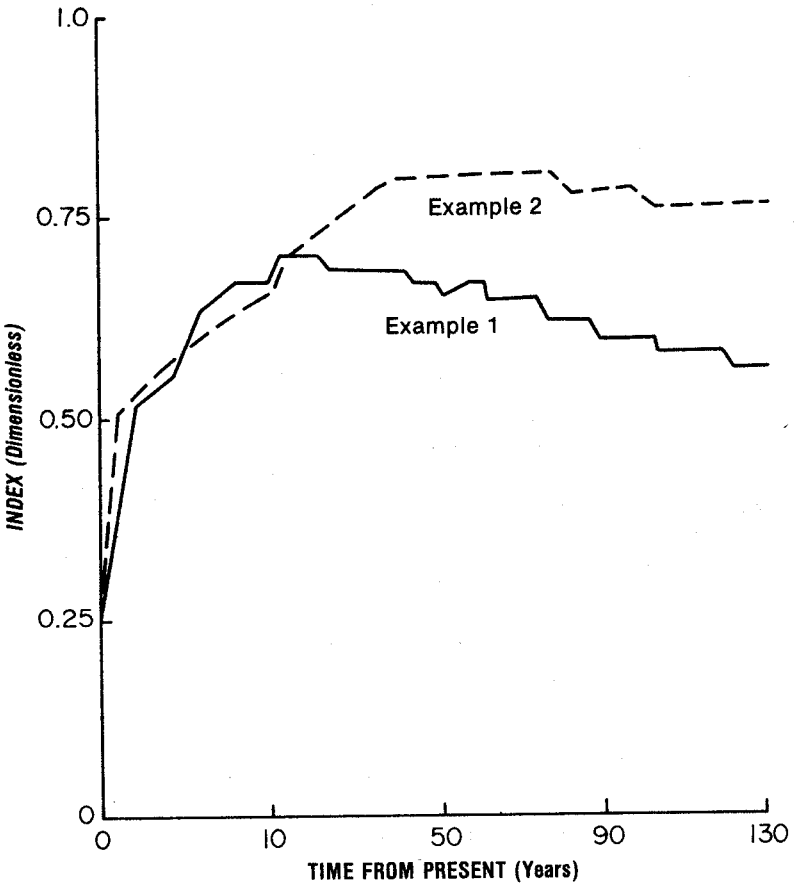

Figure 31.--Deer habitat indices projected from time zero for two silvicultural modes. (Chart is copied from a plot made by the DYNAMO compiler.)

value at time zero. For the first 10-year planning period, either example is acceptable. And, at the end of the decade, a new management mode may be chosen that is different from either Example 1 or 2. Simulating the two examples for 130 years provides some assurance that either one can maintain the deer habitat well above the initial value for many years.

The decline in the deer habitat index for Example 1 after time 10 is due to a reduction in the amount of habitat producing hard mast as the forest is transformed toward the steady state for a one-rotation period of 80 years. Deer habitat index for Example 2 continues to increase after time 10 because the superimposed rotation periods with rotations of 90 and 300 years increase both the amount of browse and hard mast. Also, the 10-acre openings used for Example 2 provide for better dispersion and use of the browse than the 25-acre openings used for Example 1 (fig. 27). The number of openings per square mile per year increases as the opening size changes from 25 to 10 acres. This change increases the dispersion of the openings, and the deer are better able to use browse in 10-acre openings than in 25-acre openings.

Habitat Algorithm for a Nongame Species

The habitat for pileated woodpeckers increases with an increase in the proportion of the area in old-growth stands. These old stands provide trees larger than 20 inches in diameter for nesting cavities; the dead trees, dead branches, and logs in old stands are a source of insects for the bird. Carpenter ants are an important source of food for this bird, especially during the winter when other insects and fruits are not available. The most frequent nesting sites are in dense, old-growth stands with large-diameter trees and many standing and fallen dead trees. If no old-growth stands are present, the pileated woodpeckers will survive in limited numbers in mature and younger timber stands. The woodpecker has been known to nest in wooded suburban areas, in developed recreation areas, along busy highways, and in other areas inhabited by people. However, the potential habitat of this

bird is greatly increased as the proportion of forest area in old-growth stands increases (fig. 32).

The absence of old-growth stands does not necessarily eliminate the potential livelihood for pileated woodpeckers. Consequently, the index is 0.1 at the zero fraction of old growth. The index increases rapidly to a maximum when 40 percent of the area is in old-growth habitat. Although the number of pileated woodpeckers may increase if the proportion of old-growth area increases beyond 40 percent, no data are available to support this assumption.

The habitat for pileated woodpeckers is assumed to decrease if more than 20 percent of the area is in seedling and sapling habitat (fig. 33). However, pileated woodpeckers may be found on snags in clearcut openings and some sapling habitats. As the proportion of seedling and sapling habitats increases to about 70 percent of the area, the pileated woodpecker habitat declines to about 10 percent of the maximum. This situation would occur for specialized management purposes such as increasing water yield by harvesting most of the area at about 20 years of age while still permitting some of the stands to survive to old-growth ages.

The waveform of the relations may differ from one geographic area to another. The important point is that specialized habitat relations can be expressed in simple white boxes (See ch. 6) and can be adjusted when new information is gathered from research and experience.

The algorithm for pileated woodpecker habitat is the product of the contributions of old growth, seedling, and sapling habitats.

$$PIL = PLI \times PLD$$

where:

PIL = index for the potential habitat of pileated woodpecker

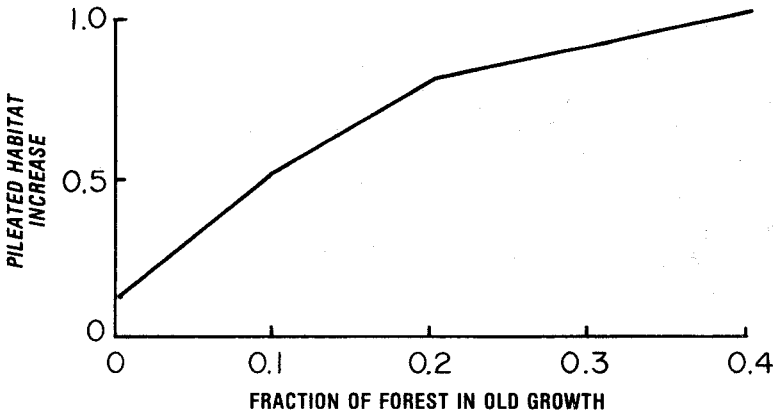

Figure 32.--The habitat for pileated woodpecker increases with an increase in the proportion of old growth.

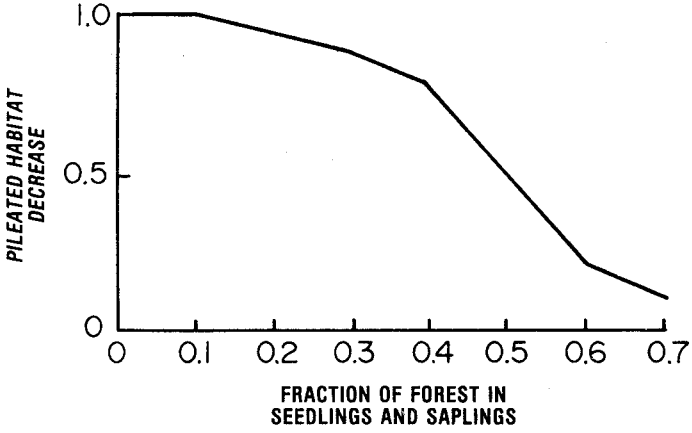

Figure 33.--The habitat for pileated woodpecker decreases as the proportion of forest in seedling and sapling habitat increases above 10 percent.

PLI = habitat increase due to old growth (fig. 32)

PLD = habitat decrease due to seedling and sapling habitats (fig. 33)

Of the two silvicultural modes discussed earlier, Example 2 shows increases in the habitat for pileated woodpeckers (fig. 34). This increase is due to the increase in the proportion of old growth--30 percent of the area is rotated through 300 years. The single rotation of 80 years, Example 1, decreases the habitat for pileated woodpecker because the accumulated old-growth habitats that were found in the initial inventory

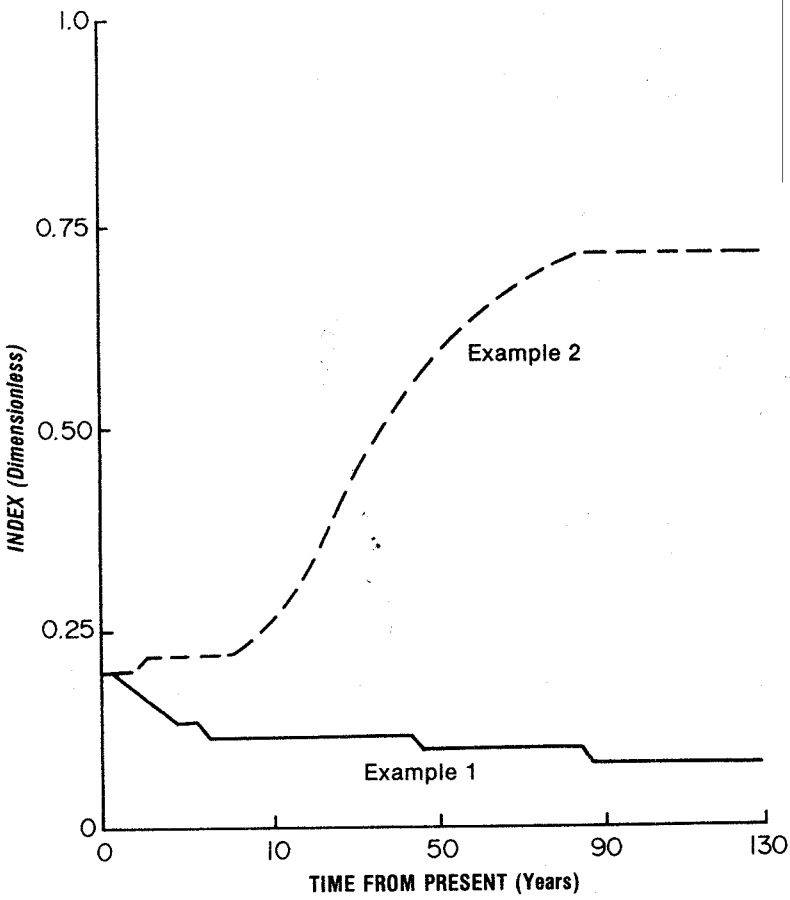

Figure 34.--Pileated woodpecker indices projected from time zero for two silvicultural modes. (Chart is copied from a computer plot made by the DYNAMO compiler.)

are harvested. Also, the 80-year rotation increases the proportion of seedling and sapling habitats to about 40 percent by the year 90. This state contributes to the decline in the potential for pileated woodpeckers.

Use of Forest Organization in Management Goals

The bionomic theories reveal a logical management structure. The new management structure is to convert the positive feedback system for organization of forest communities to a system with negative feedback loops and with a goal of bringing about a certain distribution of stands by forest types, ages, and areas. The goal is determined by selecting a biologically possible organizational state of a forest on the basis of the benefits it is likely to produce. The selected benefit combinations determine the proportional habitat distribution, a single goal, toward which management actions are to be directed. With a single goal, the complexities generated by attempts to match benefits and actions on a one-to-one basis are harmonized.

The way to achieve a habitat distribution is to organize the stands by age classes. If two or more rotation periods are used, habitats can be proportionately distributed by age classes to provide various combinations of sustained benefits. If two or more rotation periods are superimposed so that no habitat is allocated to a rotation period until the time for harvest of stands from the shorter rotation, a large number of different combinations of age classes and benefits are available.

The decision and control system links the forest manager and all interested parties to the biological systems of the forest as negative feedback loops (fig. 3). Inventories and monitorings are used to compare the forest's performance with a standard, which is the organizational state of the forest and the associated combinations of

benefits. Periodic adjustments are made in silvicultural applications, primarily harvest rates and opening sizes. The biological systems of the forest oscillate and gradually approach the chosen organizational state. However, the more likely situation is that the forest can never be brought to a steady state because frequent changes in social, economic, and political forces require frequent changes in the goal.

The decision and control system uses simulation techniques to relate the algorithms for benefits to silvicultural applications. The process allows the manager and other interested parties to use judgment, insight, and experience for subjective decisions in the strategic planning processes. The simulations provide for limited complexity in the communication of alternatives; for subjectively and rapidly discarding unacceptable alternatives; for periodically adjusting decisions as changes occur in social, economic, and political forces; for independent participation of all forestry disciplines; and for maintaining the projected alternatives congruent with the real forest.

Complexity is limited by displays of projected benefits in simple charts. Up to nine benefits can be displayed on one chart and as many charts as desired can be printed for each silvicultural mode.

All of the indices for benefits are independent of each other. There are no interaction coefficents among the different benefits. Each disciplinary area independently develops algorithms for the benefits of interests. For example, the potential timber index is developed independently of the game manager's index for deer and the hydrologist's index for water yield.

The mathematical techniques for projecting benefit combinations for different silvicultural modes are described in succeeding chapters.

Chapter 6

Cash Flows From Silviculture

Overview

Silvicultural choices include cash flows from the cultural options. Cultural options "depend on the characteristics of the tree species that make up the kind of forest type, the features of the site on which the trees are grown and the objectives and resources of the owner" (Soc. Am. For. 1981). Direct observations, simple inventories, and routine compilations of benefits and costs are the basis for identifying cultural opportunities. These simple kinds of integrations tell us most of what we need to know to apply silviculture to each stand.

Complex situations arise when silviculture is to direct the ecosystem dynamics of a forest for combinations of benefits such as timber, game and nongame habitats, water, and cash flows. Complexity, measured by the number of pairs of variables changing simultaneously, increases exponentially with each addition of a benefit to the desired combination. As complexity grows, the task of communicating relevant information among the interested parties becomes increasingly difficult: All variables can no longer be measured, coordination of silviculture among stands is almost impossible, and confusion arises among managers and other interested parties. The complexity of computing and displaying cash flows jointly with other benfits is described in "An Assessment of the Forest and Range Land Situation in the United States" (USDA FS 1980).

This chapter presents simple ways to compute and display silvicultural cash flows. A technique is described for reducing complexity and for providing clear channels of communication when directing forests to provide cash flows with other benefits.

The cash flow algorithm provides a way to analyze alternative silvicultural modes in terms of inflows and outflows of money. It also provides simple ways to project perceptions, assumptions, and insight for future changes in economic relations. These projections may be linear or curvilinear, require no complex equations, and may be adjusted daily, weekly, or at any time interval required to keep them current with new information. Common costs need not be allocated among benefits, benefits do not have to be ranked in order of their relative worth to society, and monetary values need not be justified for noncommodity benefits.

The choice of a silvicultural option is greatly simplified by choosing a flow of organizational states of a forest on the basis of the benefits likely to be produced. The simplicity of the method has several inherent advantages. All interested parties are creatively involved in evaluating silviculture options by integrating personal insights, experiences, and subjective values with quantitative data. Relations and assumptions are explicitly displayed for scrutiny in white boxes (Boyce 1982b). Information is communicated with simple charts and tables; values for decisions can be perceived quickly and explicitly.

The result is a basis for choices when the goal is for maximum monetary return or for "the relative values of the various resources, and not necessarily the combination of uses that will give the greater dollar return or the greatest unit output" (Multiple-Use Sustained-Yield Act of 1960) (USDA FS 1983a).

The chore is simplified for "specific identification of program outputs, results anticipated, and benefits associated with investments in such a manner that the anticipated costs can be directly compared with the total related benefits..." (Forest and Rangeland Renewable Resources Planning Act of 1974)(USDA FS 1983a).

Likely the most important result of all is that administrators and other interested parties can inject personal experiences and insights into the simulations. Optimal strategy is derived by subjective decisions determined by insights, value judgments, experience, and acumen of interested parties. The responsibilities of administrators are not usurped in mathematical expressions, mental models and scientifically derived relations are communicated explicitly, and people make the decisions.

Prescriptions for Silviculture

Stand prescriptions are used by silviculturists to direct ecosystem dynamics and achieve a desired organizational state for a stand. The organizational state of a stand, often called stand structure, is defined by species composition, age, stand area, basal area, timber volume, number of trees, and many other variables. The myriad of interactions between stands for sustained flows of timber, cash, water, wildlife habitats, and other benefits precludes a consistent choice of stand prescriptions without directions to achieve a single forest goal. When the goal for the forest is a single benefit, such as a kind of wildlife habitat, other benefits are viewed as constraints in the choice of silviculture prescriptions. Even if a single benefit is used as the guide for stand prescriptions, variable results are achieved for the forest. For example, the scheduling of stands for harvesting to achieve a maximum or a constrained cash flow leads to underperformance because resource allocations and policies for each stand are designed in isolation. Stand prescriptions are isolated by the perceptions for each stand of a "best practice" by silviculturists, economists, wildlife biologists, hydrologists, and other specialists. Yet the composite performance of the stands determines the flows of cash, timber, wildlife habitats, water, and other benefits from the forest.

The new direction is to integrate stand prescriptions and benefits with a single goal: to achieve and maintain a particular organizational state. Organizational states are operationally defined as the proportional distribution of stands by age, area, and type classes. Stand prescriptions under the new direction become in-place decisions directed toward a common, single goal for all specialists. The goal is achieved by controlling timber harvest rates, opening sizes, and forest type conversions. All silviculture is directed toward this goal.

The new direction expands the earlier concept of a regulated forest (Wenger 1984), which is linked to the desire for sustained yield of forest benefits. Originally conceived for timber production, the concept is to bring about a uniform distribution of age classes for a sustained yield of a certain timber type (Wackerman 1934). Recently, concern for multiple benefits has changed the goal from regulating age classes for timber alone to regulating age classes for the sustained yield of jointly produced benefits.

Single rotation periods are used to transform a forest from the present state toward a steady state in which stands are equally distributed among age classes. Superimposed rotations are used to transform a forest from the present state toward a steady state in which stands are unequally distributed among age classes. Because regulated states can rarely be achieved in practice, they are used only as a basis for setting timber harvest rates for about a decade.

The choice of a goal--a desired state of forest organization--is based on the benefits that accrue from the state. The only thing needed to make this choice is a good view of the expected benefits and their price. The system dynamics model called DYNAST provides such a view. The displays answer the general question: If we do this, what will we have? Decisions are based on

answers to the specific questions: How will this or that schedule of culture change the states of forest organization? Which silvicultural modes for the forest in question produce desirable combinations of benefits that exceed the common costs in the aggregate? Which silvicultural modes can produce desirable combinations of both marketable and nonmarketable benefits at the smallest equivalent annual costs? What monetary returns will we have? What will be the stream of benefits from the present?

Displays for Decisions

Simple charts display biologically possible combinations of benefits, including cash flows, for three silvicultural options (figs. 4, 5, 6). These displays are the medium for explicit communication of information among the interested parties. Each plot is an integration of scientifically derived relations and perceptions of mental models about responses of the forest to a silvicultural mode.

For each individual the choice of a goal is based on subjectively made decisions rather than on objectively made decisions for a mathematically identified optimal strategy. The approach is not greatly different from the process used to buy a pair of shoes. Most people do not enter a store with a fixed notion about the most desirable shoe. They look at the alternatives and make mental tradeoffs among style, comfort, utility, and price, and after a time of indecision they select a pair. Their choice is based on a good view of the merchandise and its price. This is the information conveyed in the DYNAST charts.

For the illustrations, I use an upland hardwood forest on the Pisgah National Forest in North Carolina. The forest area is called Big Ivy and contains 6,396 acres. Biological and economic consequences are illustrated for 80- and 200-year single rotations. The 80-year rotation was selected because it provides a larger sustained

yield of sawtimber by current utilization standards than any other rotation period. Because of the high sawtimber yield, a larger sustained cash flow is expected than for other rotation periods. Therefore, a forestry agency is likely to choose an 80-year rotation for similar upland forests. A 200-year rotation was also selected for illustration because after several decades this harvest rate provides old-growth stands that enhance the habitat for animals such as black bears and for pileated woodpeckers. Such a long rotation reduces timber harvest and cash flow rates.

I use the system dynamics model, DYNAST (Boyce 1977, 1979), to plot the habitat distribution, potential timber index, a selected combination of benefits, and several economic variables (figs. 4, 5, 6). Plots are made at half-year intervals for the first 10 years because this is the period of primary concern. The plots are then extended at 9-year intervals to 100 years so the long-term consequences of this kind of regulation can be examined.

As the forest is transformed toward the goal, the common denominator for all benefits, including the timber removed and the economic benefits, is the organizational state at each moment. Organizational states are operationally defined as the the distribution of stands by forest type, age, and area classes (Boyce 1978b). These stand classes, called habitats, are places to live for all endemic plants and animals. Habitats for a forest type are related to the plant and animal habitat, timber production, and streamflow.

The changes in the organizational state during the first 10 years for the 80-year rotation are: harvest of old-growth habitat (G); increase in seedling (A), 8-inch pole (D), and mature-timber (F) habitats; and decrease in 6-inch pole (C) and 10-inch pole (E) habitats (fig. 4). Also during

this time the habitat increases for eastern white-tailed deer (D), flicker woodpecker (F), and spiders (S); is stable at a low level for black bear (B); and declines for pileated woodpecker (P). Streamflow (W) also increases.

Timber production (T) is the ratio of the timber volume harvested to the volume expected if the forest were in a regulated state at the age when mean annual increment culminates. This age for the Big Ivy forest is 50 years (Schnur 1937). During the first 10 years, timber harvest (T) increases to approach the index value of 1.

Economic benefits depend on the costs and returns from the sale of timber. Computations of these benefits include stumpage values, annual overhead and timber marketing costs, capital costs, and reinvestment rates.

Figure 4 shows estimated economic benefits for the 80-year rotation in index form for four economic variables: net present value (N), benefit-cost ratio (B), equivalent annual rent (E), and realizable rate of return (R). Computation is as described by Clark and others (1979), but the values are divided by a constant for the purpose of scaling as an index for plotting. Actual values also can be plotted or printed in tables (Boyce 1977), but for this discussion we are more concerned with the general trends in the indices than with the actual values. All the economic indices begin at a low level but increase rapidly during the next 10 years. During the next 90 years some increase and some remain constant. The initial values are low because approximately $64,000 is reinvested to increase timber sales to the extent needed for an 80-year rotation. The economic benefits shown for the 80-year rotation are near the optimum achievable from timber production on a sustained-yield basis in the forest.

Let us imagine, however, that we are concerned about the welfare of black bears as well as the economic returns from timber. Let us also assume that we know that a 200-year rotation is near optimum for the bears. By year 10 the proportions of old-growth (G) and mature (F) habitats are greater and the proportion of seedling habitats (A) is less for the 200-year rotation than for the 80-year rotation (figs. 4, 5). The habitat for pileated woodpeckers (P) increases for the 200-year schedule (fig. 5) and decreases for the 80-year rotation. In year 10 all other benefits are less for the 200-year than for the 80-year rotation. After about 30 years the habitat increases for bears, deer, and flicker woodpeckers.

The economic benefits for the 200-year rotation are discouraging. Timber harvesting is low, timber production (T) is about half of the potential in the long run, and the economic indices are well below those for the 80-year rotation. Based on these projections, it is easy to conclude that the joint production of timber and habitat for black bears is too costly. This conclusion is based on regulating the forest with single rotation periods. Economic benefits rapidly decline to unacceptable levels as single rotation periods are moved away from the harvest ages that maximize the production of marketable benefits. The biological reason for this economic constraint on the joint production of benefits is that single rotation periods greatly limit the diversity of habitats by age, area, and forest type.

When the rotation period is at the age for the maximum economic benefits, all older classes are harvested and the amount of area in seedling and sapling habitats increases (fig. 4). The long periods such as 200 years provide old-growth habitats for animals such as black bears by reducing the amount of area in seedling habitat and limiting the habitat of species dependent on these conditions (fig. 5). Changing the harvest age from

the rotation period for maximum economic benefits often decreases marketable benefits faster than nonmarketable benefits are increased (Boyce 1982b). This economic constraint on the joint production of benefits can be relaxed by using superimposed rotation periods (Boyce 1977).

Two or more rotation periods superimposed on the same area transform the forest toward a steady state in which stands are unequally distributed among age, area, and forest type classes. To achieve this unequal distribution a stand is harvested at the age for one of the desired rotations. Then the succeeding stand on the same area of land is harvested at the age of an alternative rotation. In this way both the diversity and the dispersion of habitats by age, area, and forest type classes are directed at a minimum cost. To compare the results with those for single rotations, I use the following example: Stand areas pass through seedling, sapling, and other habitats until they reach the 80-year age class. At this time the manager decides to either harvest or to delay harvest until age 200. Eighty percent of the forest area is rotated through 80 years and 20 percent through 200 years. Many other combinations are possible.

The superimposed rotations change the stream of transformations. By year 10 both seedling and old-growth habitat increase (fig. 6). All benefits increase during the first 10 years, but the increases are not maximum for any one benefit. The biological consequence is increased habitat diversity and increased habitat for all endemic species (Boyce 1981).

The superimposed rotations favor the harmonious and coordinated production of joint benefits with less anticipated costs than with a single rotation period (figs. 4, 5, 6). The differences may be observed by comparing opportunity costs.

Opportunity costs for benefits in the aggregate can be compared by using the equivalent annual

rent as a measure. This measure ranks different cash flows for different time periods and ranks nonprofit producing options. For the illustration, the largest equivalent annual rents are obtained by regulating the forest for maximum timber production (table 3). When the regulation is with a 200-year rotation period, which increases the habitats for black bears after year 10, there is an equivalent annual cost. The superimposed rotations produce an equivalent annual rent in year 7 and for later years. However, the rent is less than when the forest is regulated for maximum timber production.

Economic variables for several rotation lengths and combinations can be viewed as returns for all forest benefits produced in the aggregate. Aggregated benefits include nonmarketable values such as the habitat for most endemic species. An analysis of the biological consequences need not allocate costs to each species or to each benefit. Instead, species are selected to represent classes of habitat requirements.

Displayed here are some biological and economic consequences for different silvicultural modes. The values of the various resources are considered without allocating costs to each benefit or species, and anticipated benefits are associated with investments in such a manner that the anticipated costs are directly compared with the total benefits. The displays provide information for all interested parties to select the option perceived as best. Experiences of satisfaction or displeasure are embodied in each person's perception of the option that answers the question: What benefits will I have then?

All interested parties participate in deriving the displays by injecting information, insights, value judgments, and personal experiences into the simulations. This is done with simple charts of

Table 3.--Opportunity costs for three kinds of forest regulation for the Big Ivy area, Pisgah National Forest, North Carolina, measured as an estimate of the equivalent annual rent

Years from present	Single 80-year rotation	Single 200-year rotation	Superimposed 80- and 200-year rotations
	- - Thousands of dollars - -		
1	-61	-69	-66
5	12	-28	-5
10	22	-27	5
15	26	-29	8
20	29	-31	10
100	46	-43	21

Negative values are equivalent annual costs for the time indicated.

how two variables change simultaneously or how the changes are perceived for the near future. The relations are called white boxes because the information is conveyed explicitly and in a form that can be scrutinized by all interested parties.

White Boxes for Silviculture

In the DYNAST model some benefits accruing from a particular organizational state of a forest are computed from simple relations called

white boxes, which are graphs and explained in chapter 7. For example, the current stumpage price varies with stand age class. The graph for this relation is one source of information used in the model (fig. 35). It is an explicit communication to all interested parties of relations and assumptions used to derive the displays of joint benefits. It is also a channel for resolving differences in data and opinion--it is a white box.

The waveform of the white boxes need not be described or "fitted" with mathematical expressions. The DYNAST model follows whatever waveform is drawn on a piece of graph paper and inserted into the model as a table function. The waveform can be adjusted at any time to improve congruence

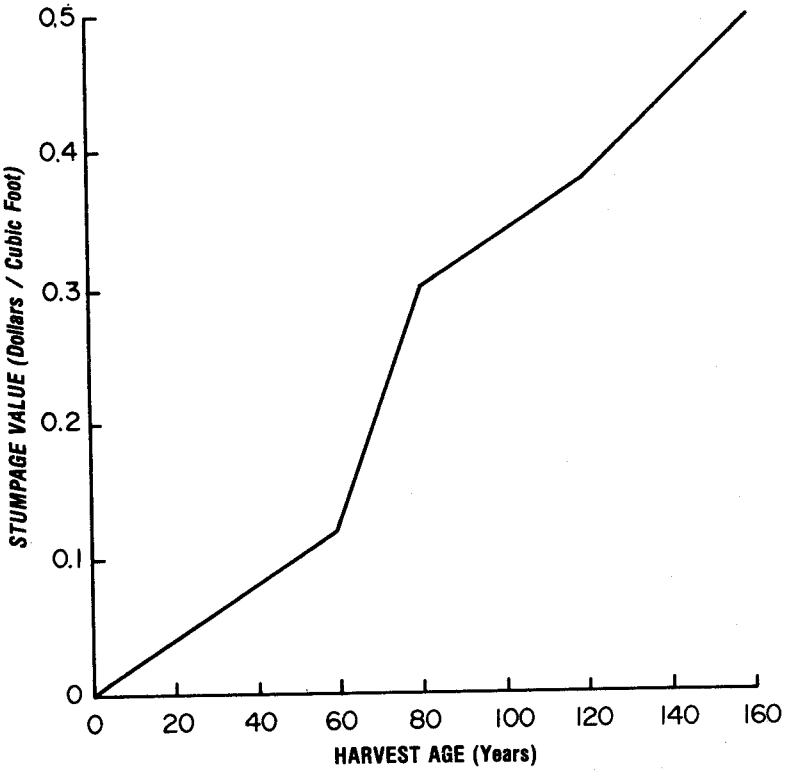

Figure 35.--Current stumpage price by harvest age of stands.

between the simulations and information from social, political, economic, and research sources.

The analytic procedure involves changing control variables in the DYNAST model to simulate desirable silvicultural options. The variables are rotation periods, opening sizes, and forest type conversions. The DYNAST model uses feedback loops to simulate transformations of the forest from the present state through a stream of states toward the steady state identified by the particular option.

The information required is a stand inventory by forest type, age, and area classes (table 4);

Table 4.--The relation of diameter, age, delay, and the inventory value to habitats for the Big Ivy area, Pisgah National Forest, North Carolina

Habitat[a]	Median diameter range	Age range	Delay	Inventory
	Inches	- - - Years - - -		Acres
Seedling	0-1.0	0-5	5	200
Sapling	1-4.9	6-35	30	1,254
Pole-6	5-6.9	36-50	15	1,843
Pole-8	7-8.9	51-65	15	740
Pole-10	9-10.9	66-85	15	1,808
Mature	11-15.9	86-120	40	366
Old growth	16+	121-300	180	185

[a]Defined in Boyce 1977, 1980.

algorithms for various benefits such as wildlife habitats, water yield, recreation, and timber volumes; and economic assumptions and parameters. Uses of inventories and noneconomic algorithms are described in chapters 5 and 8. Here I describe the use of economic assumptions and parameters that link the silvicultural options to net present value, profitability index, equivalent annual rent, and realizable rate of return.

The cash inflows and outflows depend on assumptions about the cost of cultural actions, the cost of marketing the products, and the cash received for goods and services sold. A stylized diagram illustrates how the equations are structured to compute both the amounts and the time of cash inflows and outflows as the forest is transformed (fig. 36). These auxiliary equations can be modified to fit any specific forest.

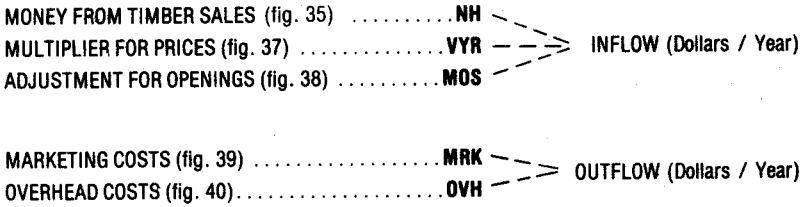

Figure 36.--Examples of silvicultural information used to calculate the cash inflows and outflows. The cash flow rates are determined by the suppositions in the white boxes and the silvicultural mode.

The inflow of money (IN) is the money received from timber sales (NH). IN is adjusted for the increased cost of harvesting small openings (MOS) and for expected changes in future stumpage prices (VYR). The money coming in from timber sales (NH) is the stumpage price at age of harvest multiplied by the timber volumes harvested. This information is from the DYNAST simulation. The current price for stumpage by age is obtained from a white box (fig. 35).

A white box is used to calculate a multiplier for stumpage price in future years (fig. 37). This multiplier (VYR) can be changed daily, weekly, yearly, or as needed to adjust the model to economic changes.

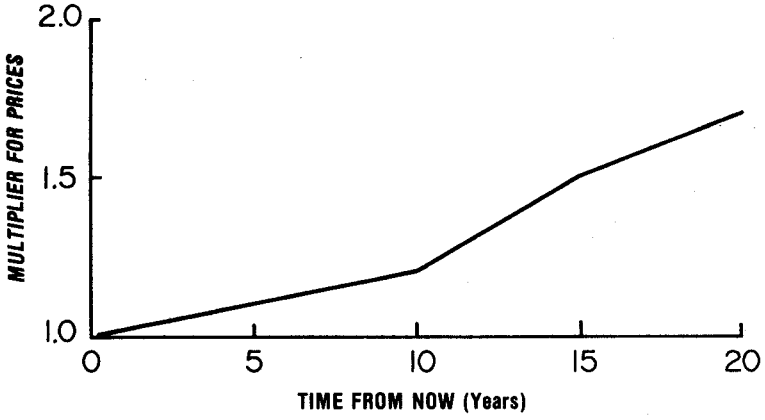

Figure 37.--The perception of future changes in stumpage prices.

The amount of money received from the timber sales is reduced when the opening size is less than 5.5 acres. Such small openings require more skid roads and logging trails and cost more to harvest than larger ones. Stumpage prices are reduced as openings decrease below 5.5 acres (MOS) (fig. 38).

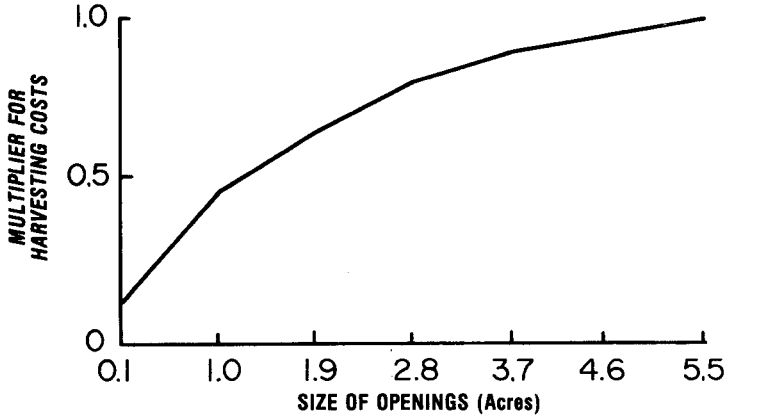

Figure 38.--Stumpage prices are reduced when openings are less than 5.5 acres.

The outflow of money is determined by costs (OT) for carrying out a silvicultural mode. This outflow is calculated for each period and includes expected decreases or increases in management costs.

One cost is for timber marketing (MRK). Marketing includes establishing boundaries, marking the trees, carrying out the sales, examining the harvest operation for compliance with the contract, and other associated costs. These costs are determined by the total area of timber sold each year (TAS), which is derived from the DYNAST model. The marketing costs (MRK) are from a graph in which the cost at time zero is determined by current experience (fig. 39). Projected costs are from insights, past experiences, and expectations for future economic changes.

Overhead (OVH) includes property taxes and maintenance costs of the entire property whether owned by forest industry, nonindustrial private landowners, or public agencies. The overhead costs (OVH) are calculated from a table that projects expected increases or decreases (fig. 40). The cost at time zero is the current cost to the landowner. The incoming dollars are the actual amounts of money received for commodities sold from the forest. No imaginary values are assigned to noncommodity items such as an assumed value for the habitat for spiders and pileated woodpeckers. Outflowing dollars are the actual amounts of money invested to maintain the forest and to transform the organizational state from the present toward a desired state. Information from the stream of transformations is used in a cash flow algorithm to compute net present value, equivalent annual rent, realizable rate of return, and profitability index.

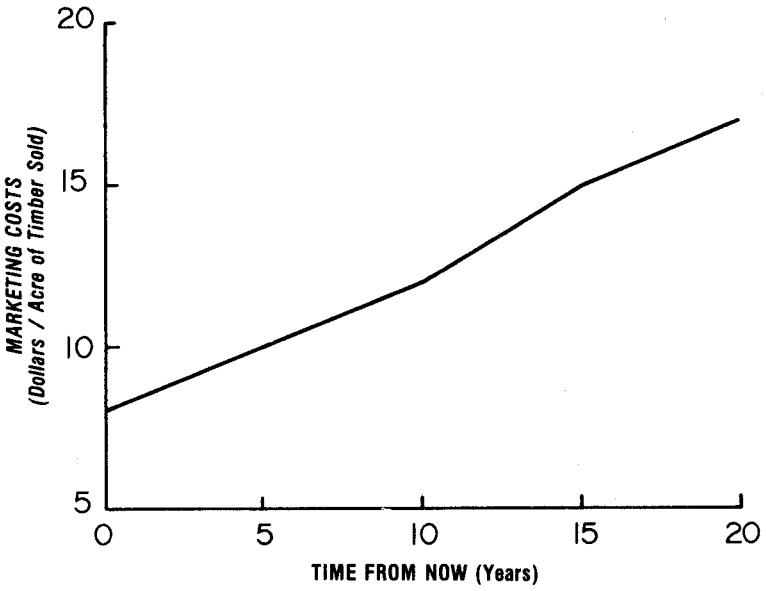

Figure 39.--Projection of marketing costs from insights, past experiences, and expectations for future economic changes.

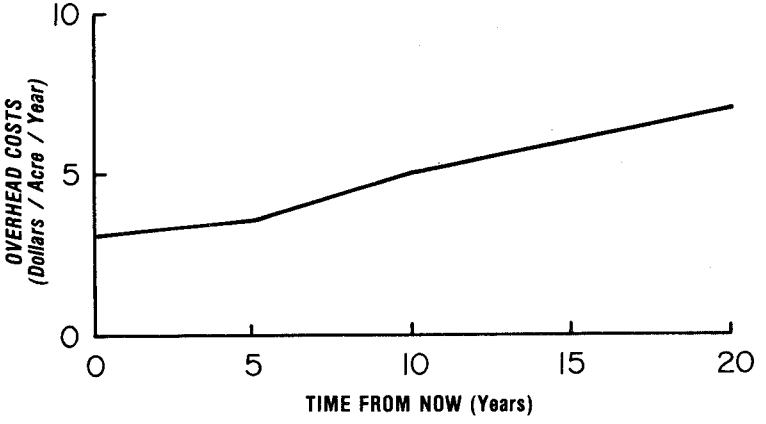

Figure 40.--Projection of expected changes in overhead costs.

White Boxes for Cash Flows

It is difficult to know what reinvestment (RIN) and discount rate (DSR) to use for evaluatin silviculture modes. The cash inflow reinvestment rates for the next several decades and the future discount rates for cash outflows cannot be accurately predicted. Because we cannot predict futur interest rates, I suggest the use of white boxes and system dynamics methods as a simple way for al interested parties to examine the effects of their perceptions of future interest rates on the aggregate costs of benefits (figs. 41, 42, 43). This allows administrators and other interested parties to inject personal experiences and insights into the displays of benefits (figs. 4, 5, 6). Some

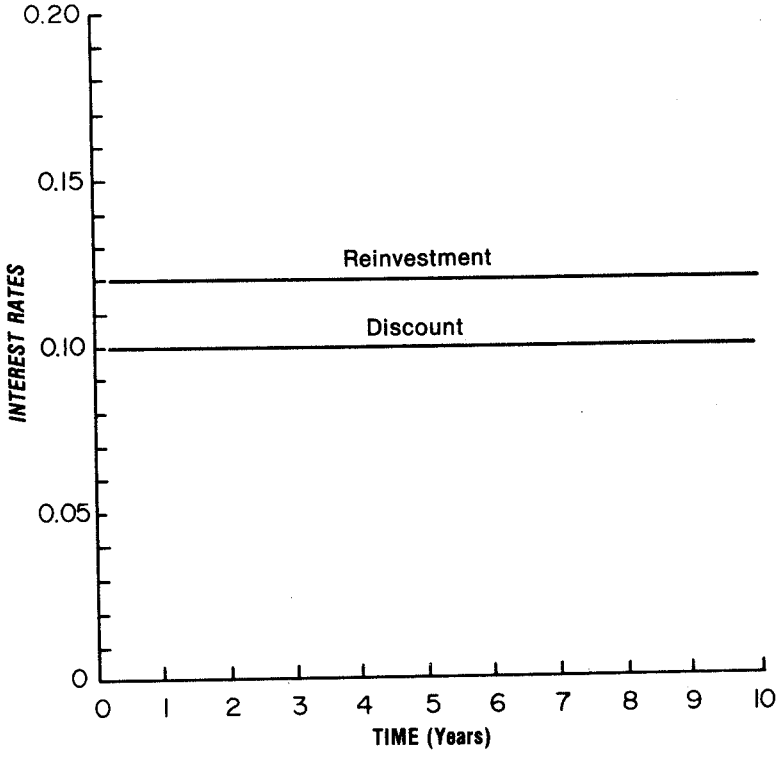

Figure 41.--Table for a constant discount rate of 10 percent for 1 years and a constant reinvestment rate of 12 percent for 10 years.

differences in perceptions by different parties can be resolved by examining the sensitivity of benefits produced by a silvicultural mode for different discount and reinvestment rates. For a particular forestry enterprise, perceived differences in discount and reinvestment rates are incorporated into the analyses by simply drawing the perceptions on graph paper. The values are inserted into the DYNAST model as table functions.

Some examples of interest rate projections viewed as perceptions of trends are: Interest rates will be constant for the next decade (fig. 41), interest rates will increase sharply in 2 or 3 years and stabilize by the end of the decade (fig. 42), and interest rates will decline for the

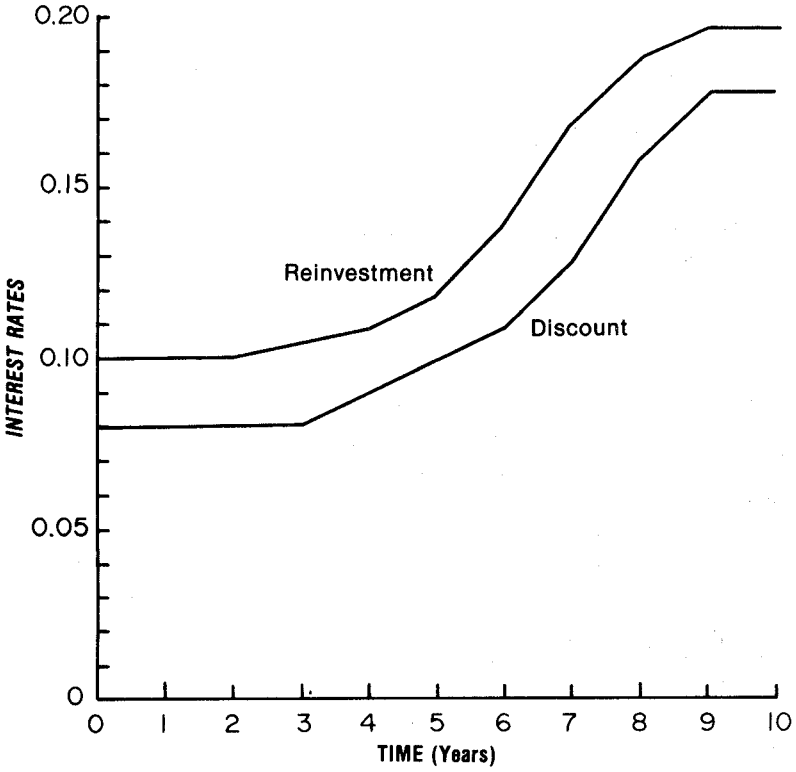

Figure 42.--A table function for increasing interest rates for 10 years.

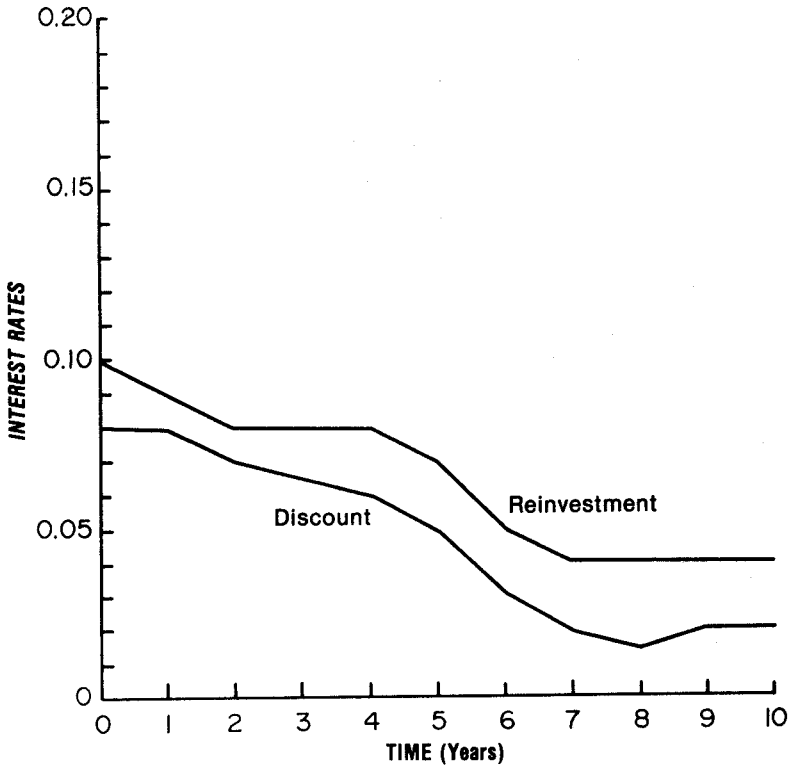

Figure 43.--A table function for decreasing interest rates for 10 years.

next 6 to 7 years and stabilize by the end of the decade (fig. 43). The perception of these kinds of trends change because new special-interest groups arise and others decline. Legislative activities change directives for the managers, change public attitudes, constrain public expenditures, and change interest rates.

Dynamic Form of Economic Functions

The indicators of economic benefits such as equivalent annual rent (fig. 4) are simulated continually as the forest is transformed from state to state. This is accomplished by translating the

economic functions into dynamic forms. The procedure is illustrated by describing how the function for continual compounding is translated to a dynamic form.

A principal (P) is to accumulate to a sum (S) at a certain time (n) and at a continual compounding rate (r). The complexity for calculating the sum is reduced by using natural logarithms, e (Clark and others 1979):

$$S_n = Pe^{rn}$$

The equation is translated into dynamic form and expressed in the DYNAMO language (Pugh 1983). A diagram suggests how the sum (SUM) increases as amounts of interest (INTR) are continually added with variable rates (RATE) (fig. 44). The level of

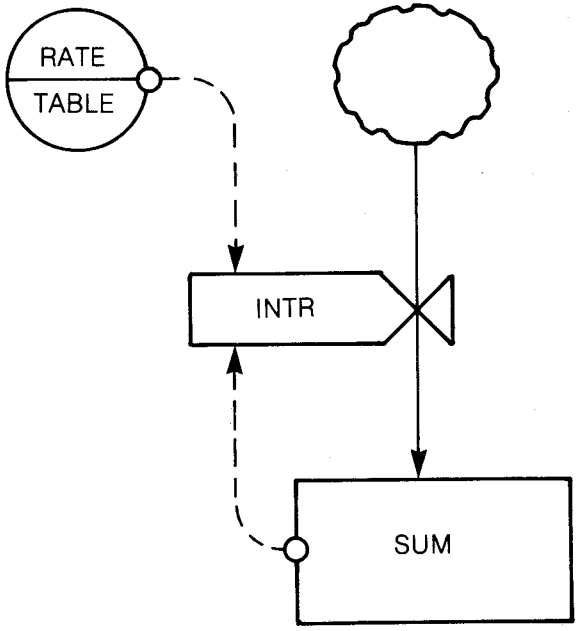

Figure 44.--Structure of the dynamic algorithm for continual compounding with a variable interest rate. The solid arrow indicates a flow of money into a "box." The dotted arrows indicate the flow of information.

money in the box increases in relation to the rate of inflow determined by the value (INTR). The rate of inflow is calculated with information coming from the SUM and the RATE table. The RATE is an interest rate derived from a white box (figs. 41, 42, 43). The waveforms of these white boxes reflect insights, experiences, and perceptions of interested parties about future interest rates. In DYNAMO language the function is written:

```
L    SUM.K=SUM.J+DT*(INTRA.JK)
N    SUM=PRNCP
R    INTR.KL=SUM.K*(EXP (RATE.K)-1)
A    RATE.K=TABHL(TRIN,TIME.K,0,10,1)
T    TRIN=.1/.1/.1/.105/.11/.12/.14/.17/.19/.2/.2
```

The level equation (L) accumulates the inflows of interest (INTR) at each differential time (DT) and adds these amounts to the SUM at the immediately preceding time (J) to calculate the SUM at the present time (K).

The equation designated by the letter N sets the value for SUM equal to the principal (PRNCP) at the beginning of the simulation.

The rate equation (R) calculates the amount of inflow in dollars for the next interval of differential time (DT). The SUM at present time (K) is multiplied by the multiplier for the interest rate at this time. This multiplier is the base of the natural logarithms (e) raised to the power of the interest rate (RATE). EXP is a function built into DYNAMO that computes e to the Ath power.

The auxiliary equation A is a table function (TABHL) that selects the interest rate for the present time (TIME.K).

The table equation T contains the interest rates perceived by the interested parties to be those expected in the future. The table values in this example are from the waveform for reinvestment rates illustrated by the white box in figure 42.

All of the indicators of potential economic benefits are transformed to dynamic form in this way. The diagram in figure 44 is one example of the basic structure for continual compounding and discounting. This structure can be modified to fit a variety of complex situations, yet the structure and the suppositions are explicitly communicated to all interested parties. Some other advantages of the dynamic form are: The reinvestment and discount rates are easily separated and projected in whatever waveform the interested parties perceive (fig. 42); the white boxes make the suppositions explicit to all interested parties; and the diagrams of structure are aids to understanding the dynamics of the model. Cash flow is a perception of money flowing from silviculture.

Conventional equations for evaluating cash flows (Clark and others 1979) are translated into DYNAMO language (Pugh 1983) and included in the DYNAST model. The equations are auxiliary to DYNAST and are not a part of the dynamic system that determines the transformation of the forest from one state to another. The controls for determining the direction and rate of forest transformation are harvest rates, opening sizes, and forest type conversion rates.

The stylized diagram of part of the algorithm structure (fig. 45) is used to illustrate the sources of information that determine the dynamic change in cash flows

where:

OTA.K = the accumulated outflow of cash (dollars) at the present time

OTR.KL = the rate of increase in OTA in the immediately following period (KL) (dollars/year)

DSC.K = continual discount divisor

DSR.K = the discount rate at present time (K)

OT.K = the outflow (dollars) at present time (K) (years); from DYNAST simulation

IN.K = the inflow (dollars) at present time (K) (years); from DYNAST simulation

INR.KL = the rate of increase in INA in the immediately following period (KL) (dollars/year)

RIN.K = the reinvestment rate at present time (K)

INA.K = the accumulated inflow of cash (dollars) at present time (K) (years)

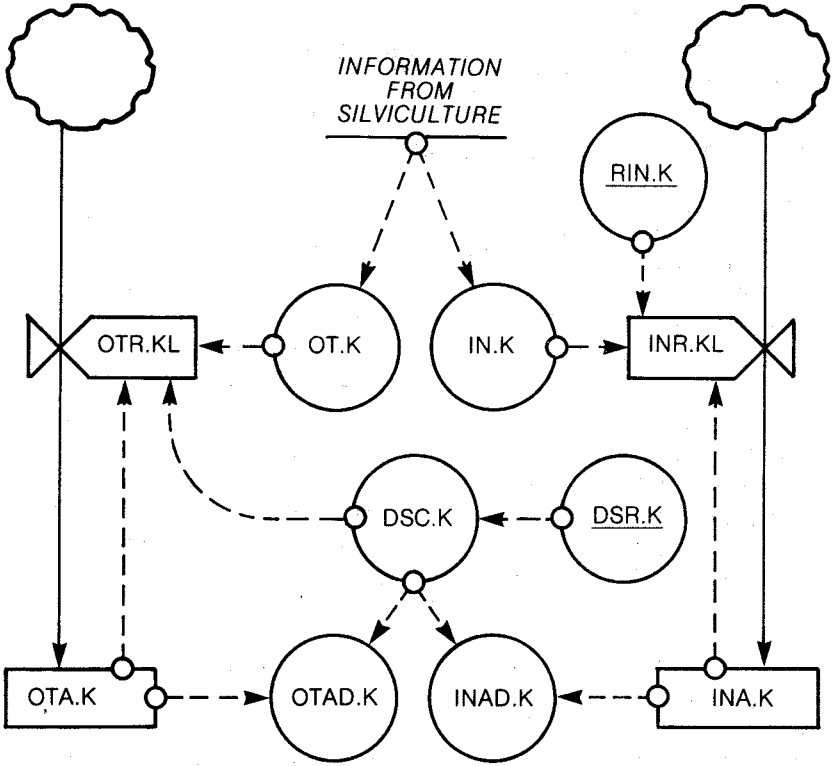

Figure 45.--The dynamic calculation of accumulated cash outflows (OTA); accumulated cash inflows (INA), which are compounded with variable reinvestment rates (RIN); and OTA's and INA's discounted to the present (OTAD and INAD) with variable discount rates (DSR).

Net Present Value

Net present value (NPV) is the sum of the present values of the cash inflows (INAD) resulting from a silvicultural mode minus the sum of the present values of the cash outflows (OTAD) required to sustain the silvicultural mode. An investment has no economic life because the intent is to perpetually maintain productivity of the forest. The net present value (NPV) is printed and plotted for each period from time zero (figs. 4, 5, 6).

Differences in simulations of net present values can be due to differences in the underlying assumptions. For example, many users of the net present value method assume that cash inflows are reinvested at the required rate of return. Other users assume reinvestment rates to be different from the required rate of return. Any assumption about discount and reinvestment rates can be used in the algorithm (figs. 41, 42, 43). An important consideration is that assumptions about interest rates be explicitly communicated when simulating silvicultural options (Rogge and Boyce 1983).

The terminal value for the project can be calculated by using either constant (fig. 41) or variable (figs. 42, 43) rates (fig. 45). Intermediate income is compounded forward to the end of each successive year by using the reinvestment rate before discounting back to the present by using the discount rate. Cash outflows are compounded forward and discounted back by using the discount rate in both directions. The most important assumptions for any project are the perceptions of interest rates; small changes may alter the cash flows of a project without affecting productions of other benefits. Thus, it is desirable to use multiple indices of cash flows and plot these indices with other benefits (figs. 4, 5, 6).

Profitability Index

This index (PI) is the ratio of the present value of the after-tax cash inflows (INAD) to the outflows (OTAD). PI ratios of 1 or greater indicate the silvicultural modes expected to yield rates of return equal to or greater than the assumed discount rate. The PI is a measure of a silvicultural mode's profitability per dollar of investment. In continual simulation, PI ranks silvicultural modes in the order of profitability at each time interval. Continual simulation by the algorithm described here indicates both the direction and the rate of change in PI.

Equivalent Annual Rent

Net present values and profitability indices are not valid ways to compare silvicultural options that have different cash flows over different periods. This problem is solved by computing a perpetual "equivalent annual rent" (EAR). This value is the perpetual annual income or cost that would yield the same net present value as a perpetual repetition of the silvicultural mode for identical assumptions about interest rates. This value is often termed the "equivalent annual income" or when negative, the "equivalent annual charge" (Clark and others 1979). For silviculture, we use the term "equivalent annual rent" because the values represent positive or negative annual rents for a silvicultural mode and do not include the values or the appreciation of the land and the residual forest.

Equivalent annual rent (EAR) is calculated by determining the equal periodic payments needed to amortize the net present value over a certain time. The procedure is to multiply the net present value at a given time by the capital recovery factor at that time (Clark and others 1979).

When the EAR is positive, the silvicultural mode yields a rate of return greater than the discount rate. The amount of return in dollars is indicated by the value of EAR. When EAR is zero, the rate of return equals the discount rate. When EAR is negative, the rate of return is less than the discount rate. The negative value of EAR, the equivalent annual rent, is the equivalent annual cost of benefits received for the period since the beginning of the simulation. Thus, EAR is a way to rank desirable combinations of benefits when sales do not equal or exceed the common costs in the aggregate and when cash flows are different for different periods.

For example, an industry may be willing to accept a cost for growing timber as a raw material when the primary source of profits is the value added by the manufacture and sale of forest products. The EAR values can be used as an index to identify the silvicultural mode that produces timber at the smallest equivalent annual cost.

Negative EAR values are useful for estimating public charges for multiple benefits that are not profit producing. The method can be used to compare different combinations of multiple benefits when the silvicultural options have unequal lives and different costs. It is essentially the same method used by many utilities for evaluating nondiscretionary expenditure alternatives and for setting rate structures. When linked to benefits, EAR for forestry is a valid way to consider "the relative values of the various resources, and not necessarily the combination of uses that will give the greatest dollar return or the greatest unit output" (Multiple-Use Sustained-Yield Act of 1960 and National Forest Management Act of 1976) (USDA FS 1983a).

For example, a government may be willing to pay for certain nonmarketable benefits such as a

wilderness, songbird habitats, dispersed recreational opportunities, and endangered species habitats. When these nonmarketable benefits are enhanced or reduced by the silvicultural mode that increases marketable benefits, no valid method exists for allocating the common costs or the dollar values of the common benefits. Calculating the EAR with the DYNAST model is a way to answer the question: "Which silviculture modes can produce the desired combination of both marketable and nonmarketable benefits at the smallest equivalent annual cost?" The bases for comparison are the EAR's and the combinations of benefits. All of these are linked by a common denominator, which is the forest's organizational state. The choice is the silvicultural mode that transforms the forest from the present state through a stream of states to produce the desired combination of benefits (Boyce 1978a, 1978b).

Realizable Rate of Return

The realizable rate of return, RRR, is the interest rate that compounds the present value of the cash flows to equal the accumulated cash inflows for the investment period. RRR value is found by solving for the compound interest rate.

Rate of return is an appealing index for comparing silvicultural options with other investment opportunities. Rate of return is a universal index and is widely understood in its simplest form. It is taken by many as a norm representative of investment opportunities in general. This situation makes some measure of return rate an important index when choosing a silvicultural schedule.

Applications to Other Forests

The methods described here can be applied to other forests. The information required is:

1. An inventory by age classes, diameter classes, and delays (table 4). (Separate inventories are needed for each kind of forest to be managed as a species type, productivity type, or other class that can be readily identified by forest workers--habitat classifications can be changed to fit the situation.)

2. A timber yield table for each kind of forest to be managed.

3. Algorithms for the benefits of interest.

4. Identification of the elements for cash inflows and outflows as a basis for computing the inflow (IN) and outflow (OT) values. (The assumed changes are drawn on graph paper as white boxes. The values for the graphs are inserted into the DYNAST model without fitting the curves to mathematical equations. The white boxes may represent perceptions for interest rates, market values, and any other insights, experiences, research findings, and information thought to influence the choice of a silvicultural option.)

The model is manipulated with the analytic silvicultural controls (Boyce 1980) to change harvest rates, size of opening harvested, and forest type conversion rate. If desired, sensitivity tests can be made for different assumptions such as interest rates and market values.

Chapter 7

Dynamic Analytic Silviculture Technique (DYNAST)

Overview

Mental models are the analytic technique most often used to make silviculture prescriptions for stands. Direct observations, simple inventories, personal experiences, and routine data compilations are adequate for choosing prescriptions for most stands. Stand prescriptions are most effective when made in-place by professionally trained specialists (See ch. 4). Yet, it is the interactions and the responses of the stands in aggregate that determine the flows of benefits from the forest. The forest may perform poorly if silviculture is applied to achieve an isolated goal for each stand rather than to achieve a single goal for the entire forest. To keep performance of the forest consistent with the combinations of benefits desired, a single goal should serve as the common denominator for stand prescriptions. When many kinds of stands are changing simultaneously, the specialist has difficulty fixing in-place decisions that direct the dynamics of the forest toward a desired combination of benefits. A list of desirable benefits may be considered a single goal for the forest; yet, this is not the kind of goal that aids the specialist to make integrated, in-place stand prescriptions. With each benefit added to the list and with each action that must be considered in making the stand prescription, complexity increases exponentially; coordination of prescriptions among stands is almost impossible; and there is confusion among the specialists, managers, and other interested parties.

The purpose of this chapter is to describe an analytic technique for reducing complexity, identifying a single goal that links the choice of stand prescriptions with the choice of forest benefits, and providing clear channels of communication

for all interested parties. The technique is called the Dynamic Analytic Silviculture Technique (DYNAST).

System Dynamics Method

Complexity, caused by many variables changing simultaneously, accounts for the uncertainties in most decision and control processes (Beer 1966; Eilon 1980). Most managers can limit uncertainty by mentally reducing to a minimum the number of variable pairs. This procedure, called minimum account (Tversky and Kahneman 1981), is a function of one's mental model and is appropriate for many situations; it is the method used to make most decisions. When the number of variable pairs changing simultaneously cannot be limited to about three by the mental model, the manager's decision and control process can be speeded up by using an aid that reduces complexity. System dynamics is such an aid (Forrester 1961). In this method the linkage of large numbers of simultaneously changing variables limits choices to a few variables that determine the dynamics of the system. Reducing the number of variables reduces complexity for the mental model and enhances the decision and control procedure (Lyneis 1980; Tversky and Kahneman 1981).

The biological basis for using system dynamics is formed by the four bionomic theories (ch. 3). These theories provide the rationale for taking actions to bring about desired organizational states. The dynamics of these changes are directed by the death of dominant and codominant trees and the resulting openings formed in the forest (fig. 46). In these openings, which are formed by timber harvest and by natural mortality, trees are regenerated to form new stands. These new stands successively transform from one kind of habitat to another and thus determine the dynamic organizational states of the forest.

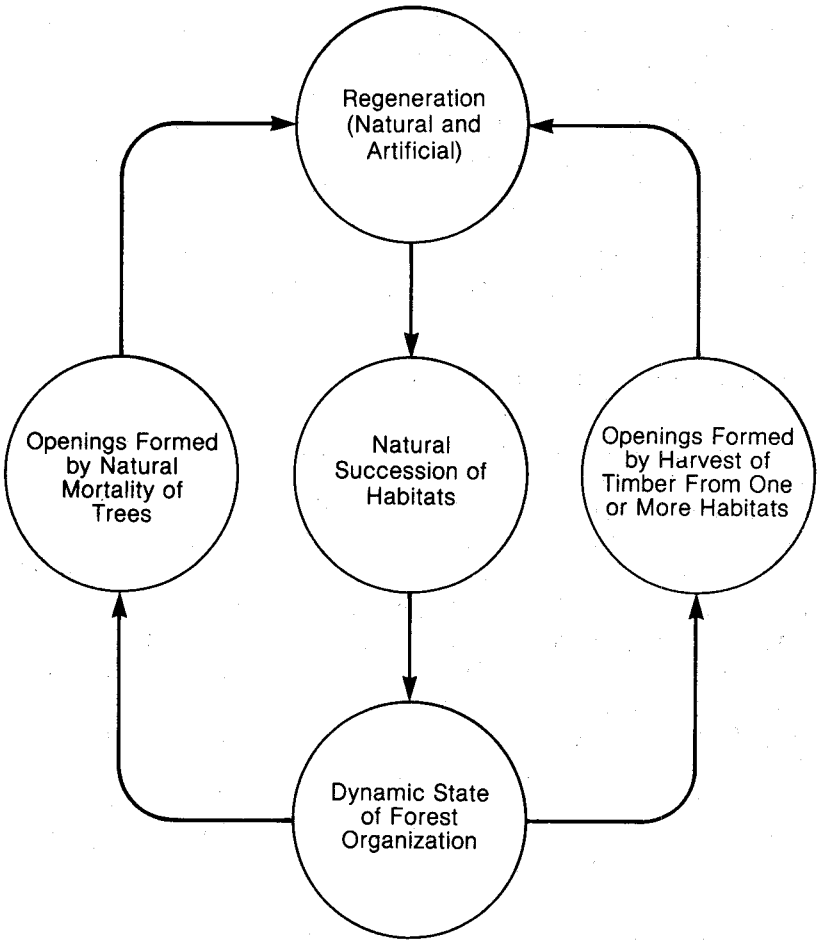

Figure 46.--Diagram of the transformation dynamics of a forest as directed by tree mortality, openings, and regeneration.

The model projects transformations in organizational states in terms of integrated flows of information, labor, energy, and materials instead of in terms of separate functions such as economics, timber, and wildlife. This approach is appropriate for biological transformations in forest communities that exhibit integrated flows of energy and materials. The structure and flow orientation is the basis for forest managers to cross disciplines without complications. For example, flows of energy, water, cash, nutrients, animal habitats, and age and area classes of forest stands transcend the interests of individual disciplines and special-interest groups. Interorganizational conflicts are reduced; decisions are interdisciplinary.

Definition of the Question

The ancient theme of forestry is conservation for the purpose of perpetually providing benefits. Included in the theme is the idea of multiple use, defined as the deliberate and planned integration of various forest uses so that uses interfere with each other as little as possible (McArdle 1962). These concepts have been conspicuous in writings and in legislation for at least 100 years (Cliff 1962; Marsh 1964). Apparently, these concepts reinforce a deeply ingrained, conservation ethic. And the ideas support strong feelings that people can live in harmony with nature. The mental models for these ideas are clearly evident in the following phrases from some legislation:

> . . . harmonious and coordinated management of the various resources, each with the other, without impairment of the productivity of the land, with consideration being given to the relative values of the various resources, and not necessarily the combination of uses that will give the greatest dollar return or the

> greatest unit output. (The Multiple-Use Sustained-Yield Act of 1960) (USDA FS 1983a).
>
> . . . specific identification of program outputs, results anticipated, and benefits associated with investments in such a manner that the anticipated costs can be directly compared with the total related benefits. . . (Forest and Rangeland Renewable Resources Planning Act of 1974) (USDA FS 1983a).

The appeal of these simple ideals is evidenced by popular phrases such as: "sustained yield," "the greatest good for the greatest number," "even flow," "regulated forest," and "living in harmony with nature." However, it is very difficult to implement these mental models. For example, a recent assessment of the forest and range land situation in the United States found that the analysis "did not deal with the complex interaction among resources because quantitative information on renewable resource interactions is limited" (USDA FS 1980:321).

The primary constraint is the lack of channels structured to integrate subjective and quantitative information for decisions by interested parties. The management decision centers on "relative values," "benefits associated with investments," and "anticipated costs...compared with the total related benefits." Complexity for a subjective choice of a perceived optimum is the issue.

A solution requires an understanding of the structure--how the component parts are linked--for silviculture and for communications among interested parties.

The forestry system (fig. 11) has a structure with the same basic elements as the car system (fig. 10). The decision and control mechanism

is the forest manager; the sensors are forest inventories, monitorings, and research; the effectors are the silviculture. The forestry system is more complex than the car system because:

1. The goal for forestry has multiple elements such as "increase the flows of cash, timber, water, wildlife habitats, and recreation opportunities," whereas the goal for the car system has one element, "go from here to there."

2. The forest managers function in response to the perceptions of many interested parties, whereas the car system functions in response to only one person, the driver.

3. The forest ecosystem is a self-organizing biological system that responds cybernetically to silviculture (Boyce 1978b), whereas the wheels of the car respond deterministically to changes in the steering wheel.

4. Delays are long in the forestry system--years and decades; but in the car system they are short--seconds and minutes. The longer delays of the forest system increase the uncertainty in the decision process about future environments.

Complexity in the forestry decision and control process limits actions for the joint production of benefits. One administrator (Thornton 1980) commented to the USDA Forest Service: "My only real fear is that we will succumb to the siren songs of the data gatherers and analysts who are entranced themselves by the power and potential of the computers. --Well thought-out and carefully directed planning can be the heart and strength of the Forest Service of tomorrow."

"Well thought-out and carefully directed" can be interpreted as a plea for reduced complexity of the mental model. Aids to simplify the mental model are needed when managers "are determined not to let the analytical calculus of decision formulation rule the decision making" (Leisz 1981).

Other signals showing that complexity in the decision processes exceeds the capability of the mental model are: (1) the difficulties encountered in attempts to allocate market values to nonmarketable products (Krutilla and Fisher 1975); (2) disenchantment with attempts to rank benefits in order of their worth to management or to society (Steuer and Schuler 1978); and (3) the frustrations of attempting to project complex matrices of resource outputs to cultural actions and costs (Alston 1979; Dyer and others 1979).

All of these analytic approaches center on the lack of quantitative coefficients for the complex interactions among resources. The questions being asked of the forest management team are: "How much timber, cash flow, water, wildlife habitat, recreation opportunities, and other benefits do you want to produce? What are the monetary values of the benefits? What are the interaction coefficients and production functions for each silvicultural mode?" (USAFS 1980:322).

My analyses guided me to ask a different question: "If the management team applies this or that silvicultural mode, what benefits will be produced?" This question is asked by and not of the management team.

In this approach, attention of all interested parties is focused on the biologically possible combinations of benefits. Choosing this or that combination of benefits establishes a single silvicultural goal. This goal, to transform the forest toward a certain dynamic organizational state, integrates cultural actions in all functional areas such as timber, water, economics, wildlife, and

recreation. Complexity in the decision and control process is limited because large numbers of simultaneously changing variables are integrated to display a few biologically possible alternatives.

A simple model jointly frames and displays sequences of outcomes for evaluation (figs. 4, 5, 6). Complexity for the mental model is limited to successively dividing groups of displays into two classes--acceptable and not acceptable--until the final choice is one of two options. Complexity for the mental model is always 1 or 2.

Advantages for individuals and organizations are: (1) Simple evaluations of a limited number of options are made by the mental model; (2) a reduced cognitive strain is placed on managers and individuals; (3) information that consequences are causally linked to acts is included from professional training, personal experiences, and perceptions; and (4) perceptions of self-interest by all interested parties are considered (Tversky and Kahneman 1981).

The system dynamics method was used to develop a solution (Forrester 1961).

System Dynamics Solution

I use system dynamics methods to place the question "If this, what then?" in the decision and control process. I expand the structure illustrated in figure 11 and use the "if" question to link the iterative process of decision and control. This process is viewed as a repetitive cycle of three events: assembling information about the state of a system, using the mental model to make decisions about the system, and using controls to bring the system to desirable organizational states. The expanded diagram, figure 3, is structured to illustrate how a forest ecosystem can be directed to produce joint benefits.

The state of forest organization is sensed by frequent inventories of stands, timber volumes, animals, and plants; monitorings are made of the ecosystem's responses to cultural actions; and research is designed to explore perceptions that consequences are causally linked to silviculture. This information is used to keep a system dynamics model called DYNAST congruent with the forest.

The "projections," represented by the diamond-shaped form, are the answers to the "if" question. These answers are displayed as charts (figs. 4, 5, 6) and tables that transmit combinations of benefits for alternative silvicultural modes to all interested parties. The question "If this, what then?" is modified by parties in the control loop. Control variables such as the timber harvest rates, sizes of openings formed, and forest type conversion rates are changed until a desired combination of benefits is projected. Any party can be involved by asking questions about the benefit displays. For the display in figure 4 a question could be: What would be the stream of benefits if harvest age were 120 years and opening size were 5 acres? A question for figure 6 could be: What would we have if 50 percent of the area were harvested at 90 years of age?

The goal for managing the forest comes from outside the system and is determined by social, economic, and political forces. These forces operate through the availability of land, labor, energy, capital, materials, and markets. Within the decision loop all interested parties participate in examining the projections of expected benefits. These projections are the basis for considering different alternatives or for deriving a consensus. A consensus results in activation of the effectors, in this case the silvicultural mode used in the control variables to project the combination of benefits selected by the parties.

The biological potential for each combination of benefits is determined by the ecosystem dynamics

that orginate through the silvicultural applications. These applications transform the forest through a stream of organizational states (fig. 46) and produce the desired combination of benefits (Boyce 1978b). I call this procedure the dynamic analytic silviculture technique. It is dynamic because the silvicultural mode is adjusted at frequent intervals to keep the benefits produced relevant to changes in the social, economic, and political forces. It is an analytic process that integrates information from the goals of all interested parties and from the ecosystem dynamics of the forest to aid the design policy by interested parties. Rather than arbitrarily setting goals such as producing so much of this and that and then allocating resources, all interested parties evaluate biologically possible goals, policies, and ecosystem dynamics. All parties also choose an acceptable sequence of outcomes.

White Boxes

Graphs, called white boxes, are used as table functions in the DYNAST model. The white boxes have value (1) as media for improved communications among managers, specialists, and other interested parties; (2) as a way to link specialists in functional areas to form interdisciplinary teams; and (3) as a way to explicitly display relations and suppositions for scrutiny by all interested parties (ch. 5).

The situation is this: Choices are derived from the values of society. These choices are mediated through the judgment and insight of managers and the institutions they represent. The white boxes are used to enhance these processes by integrating more information than would be used normally and by communicating the relations in explicit forms. Managers want communications structured for explicit displays of relations. Professionals in functional areas such as silviculture, economics, and wildlife want to be

involved in the decision and control process by integrating quantitative data with personal insights, experiences, and subjective values. Eilon (1980) and Tobin and others (1980) describe how administrators avoid the complexity of dealing with specialists by keeping mathematical analyses away from the boardrooms. Administrators, however, are also concerned about making decisions based on printouts derived from "black box" equations (Amara 1981), and they need participation from others in their decisions.

The white boxes are used to enhance administrators' judgment, insight, and understanding by integrating information from the political, social, economic, and scientific arenas. The procedure is to translate large amounts of both quantitative and subjective information into white boxes that serve as signals for explicit communication (Boyce 1981). Behavior in the decision and control process is improved. An example is the algorithm for projecting the habitat for white-tailed deer in the Appalachian Mountains of North Carolina (ch. 5).

Information about the habitat for deer in the Southern Appalachians is collected from publications, wildlife biologists, hunters, and forest managers. Suppositions are developed for the most important variables:

> ***Supposition 1***.--An increase in the area of seedling stands increases the availability of high-quality browse and soft mast.
>
> ***Supposition 2***.--An increase in the area of 10-inch pole and mature-timber stands of hardwoods increases the availability of hard mast.
>
> ***Supposition 3***.--The area of the stands influences the dispersion of forage,

mast, and cover, and influences the utilization of the forage and mast. An intermingling of small, diverse stands is beneficial.

Other considerations could be included, but I will use these three suppositions for illustration. The next step is to transform these suppositions into quantitative values that can be interrelated and closely connected to management actions.

Seedling stands are defined as stands from 1 to 5 years old. If the forest is harvested on a 100-year rotation, about 5 percent [(5 years/100) x 100] of the area would be kept in seedling stands. Changing the rotation periods changes the size of the area in seedlings and the availability of browse and soft mast. The shorter the rotation period, the greater the browse; but short rotation periods reduce the 10-inch and mature stands that provide hard mast. We know that to produce quality timber, the rotation periods must be at least 70 years. This establishes the maximum limit for the amount of area in seedlings at 7 percent [(5 years/70) x 100]. This relation is expressed quantitatively with a white box (fig. 47).

The amount of browse is maximum--has a value of 1--when 7 percent of the area is in seedlings; good-quality browse declines to a very low value--0.1--when there are no seedling stands. Some browse is always available in the older stands. The direction of the curve is not in contention; its exact shape is unknown. A straight line can be used to connect the established points, line A, but a sigmoid curve, line B, is more likely to reflect the behavior of biological systems (fig. 47). What is important is that the waveform integrate and communicate the sense of the original information. As new information becomes available, the waveform is adjusted to improve congruence between the white box and the forest.

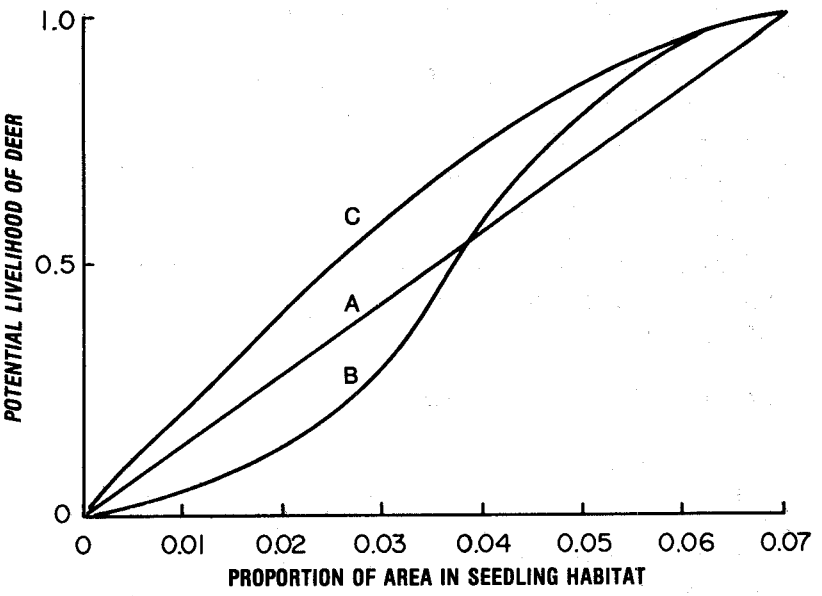

Figure 47.--A white box that explicitly displays a relation for scrutiny and adjustments by all interested parties. Lines A, B, and C are examples of adjustments made as new information became available.

Each white box is based on the best information available and is used to explicitly display relations for scrutiny by scientists, managers, resource specialists in all disciplines, and other interested parties. Any participant can ask how a change in the waveform might affect the outcome of a decision. For example, a resource manager may have evidence for a waveform similar to that of curve C (fig. 47). The effect of this change on the decision procedure can be examined with charts similar to those in figures 4, 5, and 6. In this way monitorings, inventories, research, and personal experience adapt the waveforms of white boxes to a specific forest.

Similar thinking is used to transform the second and third suppositions into white boxes.

Simple arithmetic is the computational procedure for linking white boxes. These computations as well as the information conveyed by the white boxes are important to administrators. This structure changes the mediation of society's values by integrating more information than normally would be used in making choices. The uncertainties presented by complexity and poor communications are reduced. The decision and control process is improved; the mental model is aided (Boyce 1982a; Norman 1981).

Interdisciplinary Teams

Organizations use interdisciplinary teams to coordinate the activities of different functional areas such as the physical, biological, and social sciences. Performance of the teams is often slowed because of poor communications and because the different functional areas do not have a common denominator for relating changes in variables. For example, timber values are related to the market prices for lumber; hunting values are not related to the market values of game killed. Choices, which are derived from the values of society, must be mediated with a relation common to benefits in all functional areas. Specialists in different functional areas must have a common denominator for relating timber volumes, water amounts, recreational experiences, and fishing opportunities. In forestry that common denominator is the dynamic organization of the forest (fig. 46).

As a forest is transformed from the present toward a future state, the common denominator for all benefits, including the amount of timber removed and the economic benefits, is the forest's organizational state at each moment. Organizational states are defined as the distribution of stands by forest type, age, and area classes (Boyce 1978a). Called habitats (fig. 48), these stand classes are places to live for all endemic plants

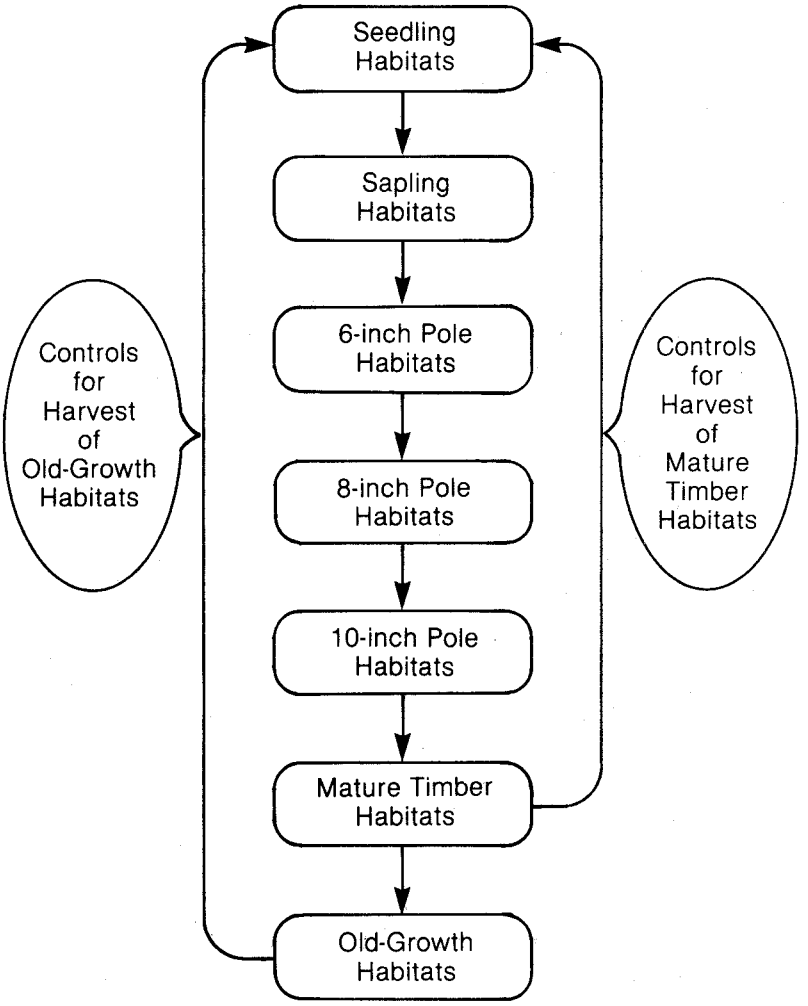

Figure 48.--Structure of the core of the system dynamics model, DYNAST. This structure, which is repeated for multiple forest types, transforms a forest from state to state.

and animals. Habitats for a forest type are related to the plant and animal habitat, timber production, streamflow, and cash flow (figs. 4, 5, 6).

Because forests can be transformed from state to state, the silvicultural goal is a certain dynamic stand distribution by various classes. This single goal is achieved by controlling timber harvest rates, opening sizes, and forest type conversions. All silviculture is directed toward this goal.

The goal focuses attention on the white boxes which are made specific for each area. Complexity and confusion are reduced to the use of simple relations that cross disciplines without conflict.

A Simple Model

From the beginning of this work my intent was to develop a simple model to aid decision and control in a forest system structured as in figure 11. My objectives were to search for an understanding of both the biological and managerial structures underlying the flows of timber, water, wildlife habitats, cash, and other forest benefits; to validate the relations that influence behavior in both the biological and managerial areas; and to search for structures and policies to increase the joint production of forest benefits. The first studies included investigations in functional areas, such as the biological potential for producing timber, water, and wildlife habitat (Boyce 1975); the application of silviculture; the functioning of interdisciplinary teams to resolve differences in demands by special-interest groups; and the managerial application of information and communication networks. These studies led to the discovery that structure in the existing functional areas enhanced poor communication among the interested parties and proliferated complexity for administrators.

This finding was a clear signal that simulating the structure illustrated in figure 11 could achieve the first two objectives and may reveal variables controlling the dynamics of the system, but it could not assure the third objective. The difficulty is that such an encompassing model would have to include suppositions about the behavior of mental models for a diverse group of interested parties. To discover and project the dynamics of someone else's mental model is difficult because the structure is not visible, and observable responses are often different from the modeler's way of perceiving the forest. My perception was that the most important negative feedback loops in the forestry system were in the communications networks that led to the choice of a series of cultural actions and in the communications networks that professionals in the functional areas used to apply cultural actions. These networks cannot be discerned and mathematically modeled to be congruent with the real forest because the behavior of the system is dependent on in-place decisions of mental models.

The study plan was changed to develop a simple model that would aid in-place decisions for administrators, professionals, and other interested parties. The constraints to be relaxed were poor communication and proliferating complexity. To find a useful structure, the diagram in figure 11 was modified many times until the one in figure 3 was selected. This choice of structure for the model links management processes to practices familiar to trained foresters (fig. 48). When a forest habitat is harvested, natural or artificial regeneration establishes a seedling habitat which will transform through size classes at a rate that can be accurately predicted on the basis of many years of experience.

The model is started with information from an inventory of the real forest. Feedback loops in

the model determine the harvest rates to be used in the real forest to transform it toward the desired organizational state.

This kind of transformation is easy to direct by scheduling the timber harvest rate, the species regenerated, and the stand area. Because of the uncertainty of dynamics in large ecosystems, we cannot go much further than this in prediction and control. However, it is a degree of control that is highly useful to forest managers. The pattern of harvest followed by predictable succession through age classes can be used to create a certain organizational state for the forest--a proportional distribution of stands by age, area, and type classes. And the organizational state largely determines the kind and proportion of benefits available from a forest, such as timber, wildlife habitat, and cash flow (Boyce 1980).

Chapter 8

Structure of the DYNAST Model

Overview

Models are perceptions of the structure and functioning of some aspect of reality. Any decision or action can be modeled. The model may be mental, such as a plan for a day's activities; physical, such as a floor plan for a building; or mathematical, such as an equation or mathematical algorithm. Simple models, such as highway maps, can be used without extensive documentation. When models become large, computers can be used to link large numbers of equations and algorithms and to display results as charts, diagrams, and tables. The computers and the equations are tools used to organize, structure, and display information in a way similar to how pencils are used to display information in the form of words.

Simulation models are ways to use algorithms in a computer to describe the dynamics of a system. The model contains algorithms representing elements of the real system. These elements are linked as in the real system to emulate the transformations in states of the system as the environment changes. Continual simulation models are appropriate for systems, such as a forest, that have continuous flows of energy and materials and the system cannot be stopped to study discrete changes. Such simulations use finite-difference equations that approach the differential equations of continuous flows. Probably the best-known compiler for translating and running continual models is DYNAMO (Pugh 1983).

DYNAMO was developed by the system dynamics group at Massachusetts Institute of Technology for simulating behavior in business, economic, and social systems (Forrester 1961). It is used here for forest systems to aid the decision and control

process. DYNAMO concentrates the user's attention on understanding the causal relations that lead to behavior and requires little understanding of the complex computer requirements evident in most mathematical models. This makes the DYNAMO model easy to understand and manipulate by specialists in functional areas such as soils, hydrology, economics, silviculture, wildlife, recreation, and inventory. Error analysis is thorough and error messages are expressed in easily understood terms.

DYNAST is written in the DYNAMO language. DYNAST simulates familiar management and silvicultural processes by referencing outcomes to perceptions in the mental models of functional specialists and managers. The structure of the model includes not only the biological aspects of the forest but also the social, economic, and political forces that dominate the choice of decisions.

Features

DYNAST has several important features that aid managers to direct the behavior of forests. First, the theory of feedback systems is used to integrate information from quantitative sources and from mental models to form a cybernetic structure. Second, four bionomic theories are used to organize biological information to reflect changes in the forest being managed. Third, information that would otherwise stay in verbal, descriptive form is converted to an explicit display of interrelations that can be used to make management decisions. This means that all the assumptions, translated from research and experience, become quantitative and are displayed in interactive relations in the same way that they are perceived to occur in the real forest. Fourth, only easily obtainable information typically available from forest inventories is required to operate the DYNAST model.

Inventory

Inventories at periodic intervals provide information for starting the model, keeping the model congruent with the real forest, and changing silviculture in relation to social, economic, and political changes. An accurate, up-to-date inventory is essential for any kind of a plan. Yet, the inventory should not be complex. Unnecessary detail should be avoided. For example, certain minimum data are required to classify stands by age, area, diameter class, and forest type.

The stands are grouped according to diameter class of the dominant and codominant trees. These groupings are chosen to divide the continuum of stands into categories related to the plant and animal habitat.

The Big Ivy Forest

This forest is in the Big Ivy Creek Watershed, near Barnardsville, Buncombe County, NC. Timber sales have been limited for many decades because practically all of the area was harvested about 1900. Only a few of the original stands were not harvested. The initial harvest left many low-value trees, which were crooked and decayed because of long suppression in the understory. Occasional wildfires burned some areas. Harvests in recent decades have been scheduled to remove the aged, previously suppressed, and poorly formed trees; to salvage fire-injured trees; and to thin the young stands that were accessible from existing roads. Some timber sales were designed to increase age-class diversity.

The predominant forest type is upland oak-hickory, and all stands contain approximately the same species (Boyce and Cost 1978). Small areas can be classified as beech-maple, maple-buckeye, yellow-poplar, and other types, depending on definitions and interpretations. Spatial changes in

both species and site index values are continuums that vary over distances of 50 to 100 feet. For planning purposes, only a single forest type and a single productivity class are recognized. Elevations range from 2,500 to 3,500 feet. The habitats for the Big Ivy forest (table 14, fig. 48) are defined as follows:

Seedling habitats.--Stands with median diameter of dominant trees less than 1 inch.

Sapling habitats.--Stands with half of the dominant and codominant trees between 1 and 5 inches d.b.h. and a few scattered large trees.

Pole habitats.--Stands with half of the dominant and codominant trees between 6 and 11 inches d.b.h. Pole habitats are classified by 2-inch diameter classes as pole-6, pole-8, and pole-10 habitats.

Mature-timber habitats.--Stands with half of the dominant and codominant trees between 11 and 16 inches d.b.h.

Old-growth habitats.--Stands with half of the dominant and codominant trees larger than 16 inches d.b.h.

Ages are not directly related to median diameters, but young trees are usually smaller than old ones. Diameter data are important primarily for relating the habitats, which are based on diameter classes, to a range of ages. These ages indicate transformation rates of one habitat, for the median number of stands, to naturally succeed to another one. This succession coupled with the timber harvest rates determines the flows of stands from habitat to habitat and, therefore, the transformation of the forest from state to state. These basic transformation rates can be modified with

thinnings, use of genetically different trees, drainage of the soils, and application of fertilizers. Yet the primary managerial controls are the rotation age, the opening size formed, and the conversions of forest types.

Transformation of a Habitat

The reserves in the mature-timber habitat on the Big Ivy forest are found to be 306 acres of unsold timber. Mature-timber habitat sold, still standing, and scheduled for harvest is 60 acres. Diagramatically the mature-timber reserves (RSR) are represented by a rectangle (fig. 49). This habitat has an age range from 86 to 120 years and a delay for succession to old growth of 35 years. The mature-timber reserves consist of stands arrayed by age from the 86- to the 120-year age class (fig. 49). The average area for each 1-year age class is about 8.7 acres (306 acres/35 1-year age classes). An inflow of stands (TIN) comes from natural succession of 10-inch poles to mature timber; an outflow of stands (SEL) occurs at a rate determined by the timber sales rate. The timber sales rate (SEL) is a variable that is determined by a negative feedback loop. This loop has the goal of maintaining an amount of mature-timber reserve to meet the sales rate desired by management. This sales rate is controlled by management with the control constant termed "rotation age." This is the approximate age that management wants the timber sold. For example, if management wants the timber sold at age 100 years, the negative feedback loop increases or decreases the sales rate to bring the amount of mature-timber reserves to the level required to sustain the sales rate.

The negative feedback loop is described in chapter 2. The state of the system is the amount of mature-timber habitat in reserves (RSR) and the goal is the equilibrium amount of reserves (EQ). This amount is determined by the rotation period set by management. For example, the Big Ivy has

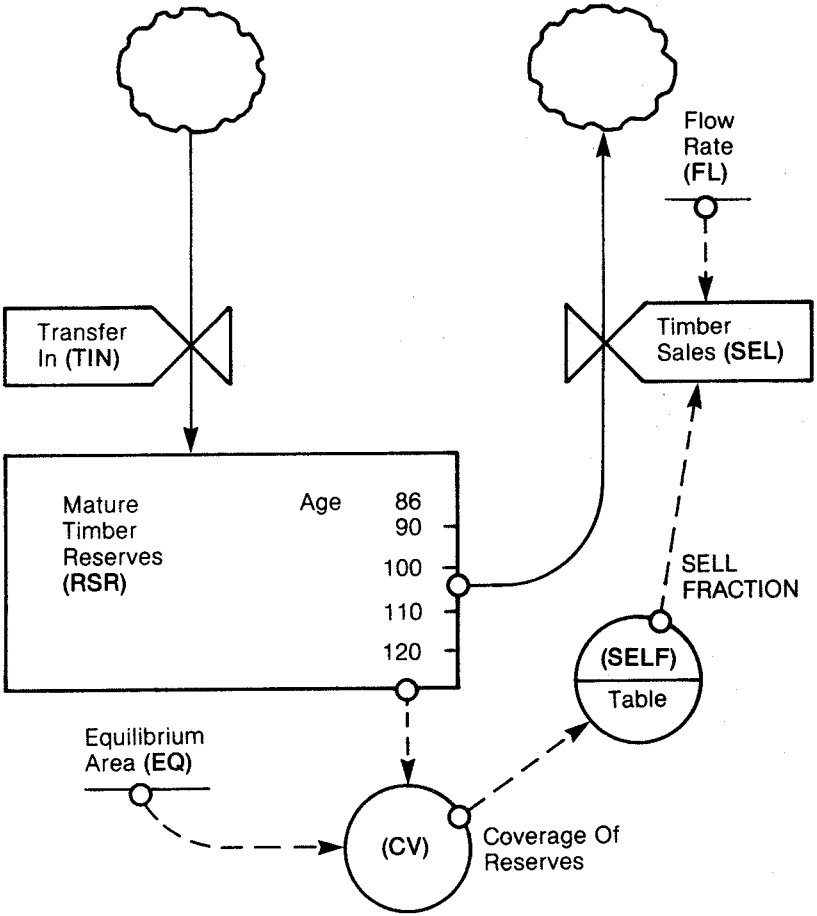

Figure 49.--Diagram of the DYNAST model structure used to transform a habitat by harvesting timber.

6,396 acres (table 4). If the rotation period is 100 years, the annual area harvested at steady state would be about 64 acres ((6,396 acres)/100 1-year age classes). This is the flow rate (FL), the average annual flow of stands across the 1-year age classes for the harvest age. Within the reserves for mature timber there are fifteen 1-year age classes between 86 and 100 years. Therefore, the equilibrium reserves for a 100-year rotation is about 960 acres (64 acres/year x 15 years). This

960 acres is the equilibrium area (EQ) for mature-timber reserves (RSR) when the forest is in a steady state for a 100-year rotation period. The equilibrium area is the goal for the negative feedback loop, which is determined outside of the loop by management's choice of a rotation period.

The decision mechanism in the negative feedback loop increases or decreases the timber sales to maintain mature-timber reserves (RSR) at the equilibrium area (EQ) for a given harvest rate. The coverage function (CV) compares the amount of mature-timber reserves (RSR) with the goal (EQ) and produces a ratio that expresses the difference. When the ratio is 1 or greater, timber sales (SEL) are equal to the flow rate (FL) for the rotation selected by management. When the coverage ratio is less than 1, the timber sales are reduced proportionally until the mature-timber reserves have returned to the equilibrium amount. This scaling of sales is done with a table function called the sell fraction (SELF). This table can be adjusted to increase or decrease sales at different rates relative to the amount of mature-timber reserves.

The transformation described by the diagram in figure 49 is familiar to many people in forestry because the concept has been the basis for regulating forests for more than 200 years. The concept of a regulated forest is linked to the desire for a sustained timber yield. The method for achieving this sustained yield is to divide the forest area by the rotation age, which is selected on the basis of the value, kind, and amount of timber desired. The intent is to bring about a uniform distribution of age classes. In practice, regulated states have been of interest primarily as a basis for setting timber harvest rates for about a decade because the regulated state can rarely be achieved. The regulated state is difficult to achieve because of changes in the standards for use of the timber, the economic conditions, and the rotation period.

An important innovation is the use of the negative feedback loop, which adjusts the sales rate relative to the amount of timber reserves available for sale. This adjustment can dampen the oscillations in the timber reserves and aid management in responding to changes in economics, utilization, and other external conditions. Familiar procedures are structured to aid the decision and control process more effectively than the structures used in the past.

Symbols and Equations

The following information is based on the "DYNAMO User's Manual" (Pugh 1983) and the introductory text by Richardson and Pugh (1981). Concern here is to provide minimum information for understanding the structure of the DYNAST model.

Before the model is formulated in mathematical expressions, it is important to analyze the structure of the system being studied. The structure of the simulation model should be controlled by the purpose of its use. For DYNAST, the purpose is to aid mental models for improving decision and control for forestry systems (ch. 1). Analyses (chs. 3, 4, 5) are used to conceptualize a structure (ch. 7) for the model to do what is desired.

Formulating component parts of the model is best done by first diagramming the flows of information, materials, and energy; and second, challenging these structures before equations are written. The challenging questions may include: Where are the feedback loops? Do the loops function on the basis of valid arguments about the real world or do they mimic an empirical history? Does the model convey the dynamics of variables essential to what is desired? Are the loops a complex of valid arguments but superfluous to what is desired? Figures 44 and 49 are diagrams that have been reduced to the simplest form to illustrate the

dynamics of variables essential to the desired use of the model. These diagrams may appear simple and easy to conceive; yet, they are the result of many stages of questioning, analyzing, and restructuring the linkages and the flows of information and materials.

Each of the symbols has a special meaning. Accumulations of flows are represented by a rectangle (fig. 49). These rectangles are called boxes, stock, state variables, or levels. The term "level" invokes images of various ranks of materials or information as the flow rates change. For example, forest stands flow into the mature-timber reserves at a certain rate and flow out at some desired harvest rate. The initial inventory and the differences in the rates determine the "level" of mature-timber reserves. Equations for these rectangles are called "level equations," are designated by the letter L, and are mathematical expressions for the integration process. In equation form this can be stated: A quantity now is equal to the earlier quantity plus elapsed time multiplied by the rate of change. In DYNAMO language the equation for mature-timber reserves is written:

```
L     RSR.K=RSR.J+DT*(TIN.JK.-SEL.JK)
```

The . means a subscript follows the name of the variable. Mature-timber reserves for the present are subscripted with the letter K; for the earlier quantity the subscript is J. The computation interval is called DT, also designated the differential time. The inflow and outflow occur between the time JK; thus, it is the subscript for the rate variables. The difference between the inflow and the outflow is the rate of change during the time DT. The relation of the subscripts to the computation interval is illustrated in figure 50.

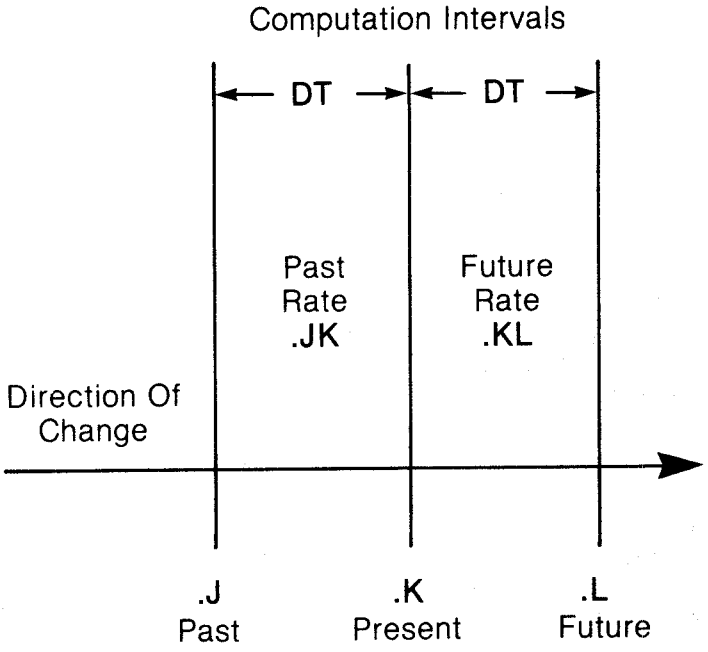

Figure 50.--Diagram illustrating the relation of the subscripts in DYNAMO equations to the computation interval (DT) and to the direction of change in time.

The primary use of N equations is to assign initial values to a level variable such as RSR. For example, the initial inventory of the Big Ivy area found 306 acres in the mature-timber reserves. When the model is begun at time 0, the 306 acres are inserted into the level equation RSR with the initial equation written:

```
N       RSR=306
```

The inflow of stands (TIN) from the 10-inch pole class of habitats (fig. 48) is a simple differential rate dependent on the amount of land area in this habitat. This amount of land area (SL) is divided by the delay in years (DSL), which is the average period for succession through this habitat. The rate for transfer in (TIN, as shown in fig. 49)

is diagrammed as a stylized valve to indicate a changing flow rate. The rate equation is designated by R. The equation is written:

```
R       TIN.KL=SL.K/DSL
```

The inflow of stands (TIN) is subscripted KL because the computation of rates is for the next time interval (fig. 50). The circles in the diagrams indicate equations auxiliary to the rates and are designated A equations. This procedure separates the rate changes into parts that can be easily envisioned, understood, and changed to make the rates consistent with the real world. The coverage of reserves for mature timber (CV) is auxiliary to the rate equation for timber sales. The coverage at the present time is simply the reserves at the present divided by the equilibrium area for the rotation period desired. The equation is written:

```
A       CV.K=RSR.K/EQ
```

The equilibrium area is a constant that is symbolized in the diagram with an underline and the equation is designated C. For a 100-year rotation the constant value for EQ is 960 acres; this is written:

```
C       EQ=960
```

The sell fraction is an auxiliary equation based on a table designated T. The circular symbols for table functions have one or two horizontal lines and often the name of the function and the word "Table" to distinguish these kinds of auxiliaries. The equation for the auxiliary SELF is written:

```
A     SELF.K=TABHL(TSLF,CV.K,.4,1,.2)
```

The sell fraction at the present time is computed by a table function called TABHL. Certain

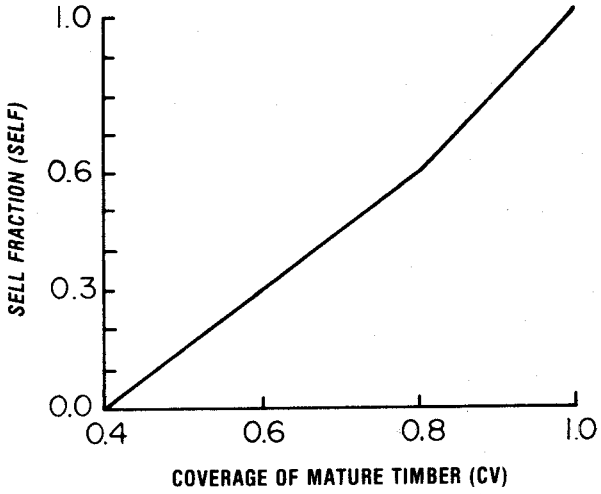

Figure 51.--A white box illustrating one policy for changing the sell fraction when mature timber coverage is less than 1.

arguments must be given in an exact sequence between the parentheses. TSLF is the name I gave the table that I wanted to use; CV.K is the independent variable that I wanted to use for reading a value from the table; the table contains values extending from 0.4 to 1 in units of 0.2. Next, the dependent variables in the table are given with a T equation.

```
T       TSLF=0/.3/.6/1
```

The tables should be drawn as white boxes (fig. 51) because the slope and the waveform of the curves reveal more information about how the function works than does the T equation. Also, drawing the white box provides a medium for communication, a display for scrutiny, and a way to reduce the chances for making a mistake in recording the table in the model.

The auxiliary SELF functions this way. When the coverage ratio (CV) has a value 1, the value of SELF, taken from the table, is also 1. When the mature-timber reserves (RSR) are less than the equilibrium area (EQ), the coverage is less than 1.

For example, assume the coverage had a value of 0.8. Then from the table, the value of SELF would be 0.6. If the amount of mature-timber reserves declined to 0.4 or less of the equilibrium area, the sell fraction would be 0 and no timber would be sold until the coverage increased to more than 0.4. The TABHL interpolates between values given in the table. The independent variable in this example, CV.K, can exceed the limits of the table (TSLF) without causing an error message. Beyond the limits of the table, TABHL takes the last value in the table. For this example, the timber sales rate is limited to that specified by the rotation period desired when the coverage is greater than 1.

The timber sales rate is determined at each computational time by the sell fraction and the flow rate, which is a constant determined by the desired rotation period (ROT). The flow rate (FL) is calculated by dividing the area of the forest (TAH) by the desired rotation period. This constant can be computed with an N equation if the values for TAH and ROT are inserted into the model as constants. The equations would be written:

```
C     TAH=6396

C     ROT=100

N     FL=TAH/ROT

R     SEL.KL=SELF.K*FL
```

The sell fraction functions through the negative feedback loop to increase or decrease the timber sales rate according to the amounts of mature-timber reserves. Furthermore, the table in the auxiliary loops stops timber sales when the reserves are low but does not increase sales above the desired flow rate when reserves are high. One can direct this negative feedback loop to do many

different things by changing the limits of the table and the waveform of the curve. An important consideration is that all interested parties have access to the white boxes and thus are able to interpret the displays and the tables produced by the model.

Transformation of a Forest Type

Natural succession and timber harvest transform forest types from state to state. When the same species is regenerated, the transformations change the distribution of age and area classes. If silviculture or natural succession changes the species regenerated, the result can be an increase in habitat diversity and an important change in the availability of benefits. These transformations can be tracked with the DYNAST model.

Seven habitat classes are used in the model (fig. 48). This number is selected on the basis of the relations of each habitat class to one or more benefits. For example, mature-timber reserves (fig. 49) was selected because the amount of this habitat determines the amount of mature timber that can be harvested. The seedling habitat is important as a source of food for many animals. The grouping of age classes to define habitats for use in the model is based on the usefulness of each class for projecting benefits. For example, if a single rotation period is used to harvest a kind of mature timber, a rather simple structure with six habitat classes is followed (fig. 52). I use the illustration of harvesting natural loblolly pine stands and replanting with genetically improved pine seedlings (Boyce 1975, 1977).

Excluding roads, developments, and nonpine stands, the inventory of the Big Pine forest on the Coastal Plains of North Carolina reveals an unequal distribution of age classes (table 5). The median diameters for the range of ages are

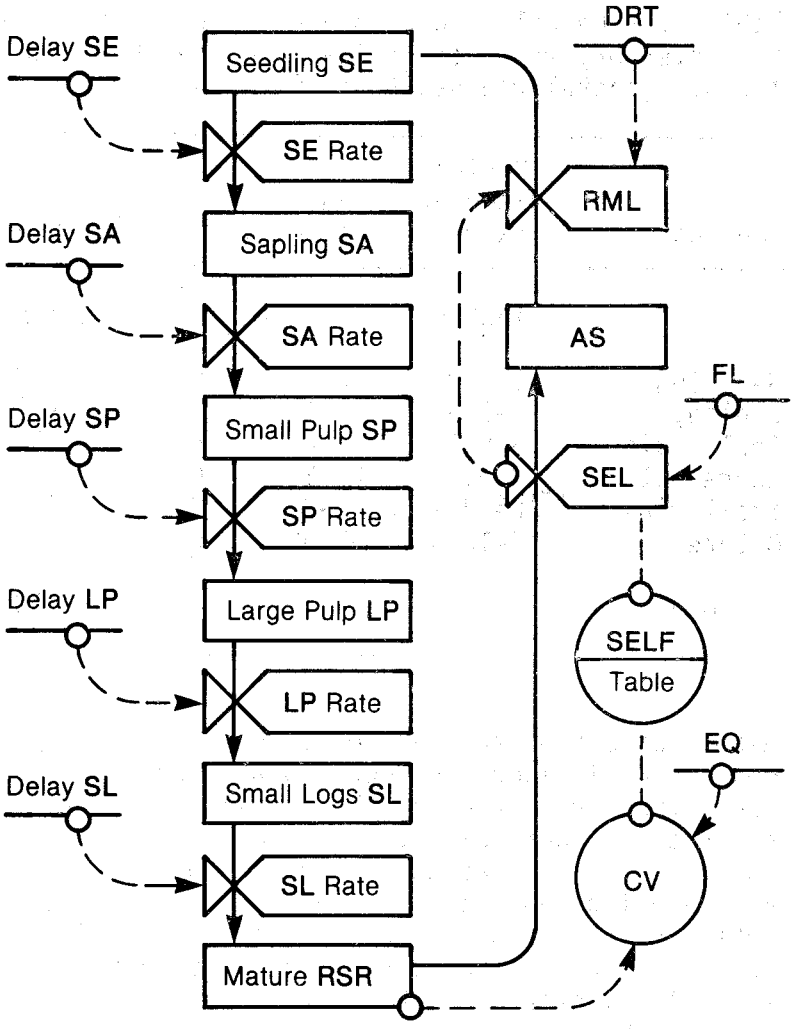

Figure 52.--Diagram of the core model structure with six habitat classes for a pine forest (cf. with figs. 48 and 49).

based on local yield tables and on natural stand succession. This information is used to choose the habitat classes, which then determine the delays. Because of unequal habitat distribution, the flow rate for a 35-year rotation would require about 4 decades to reduce the reserve volumes of mature timber to the equilibrium amount (EQ).

Table 5.--The relation of diameter, age, delay, and the inventory value to habitats for the Big Pine forest, Coastal Plains, North Carolina

Habitat	Median diameter range	Age range	Delay	Inventory
	Inches	Years		Acres
Seedling	0-1.9	0-8	8	0
Sapling	2-3.9	9-15	7	122
Small pulp	4-6.9	16-20	5	38
Large pulp	7-9.9	21-26	6	10
Small logs	10-12.9	27-34	8	261
Mature	13-15.9	35-60	26	362
Total			60	793

Also, harvest of the mature stands in about 2 years would rapidly increase seedling and sapling stand area, thereby increasing the oscillation of age class and timber volume. The model is structured to moderate oscillations in the amounts of mature and seedling habitats by regulating the harvest rates according to the rotation age set by forest managers. Within the biological constraints--the initial inventory and the growth rates--the negative feedback loop achieves a uniform flow of timber to be harvested at about the desired rotation age.

The feedback loop, the mature-timber harvest (table 5), has already been described. A positive feedback loop is now added to the model to track changes in the areas by habitat classes.

Timber is not instantaneously harvested at the moment of the sale. There is a delay occasioned by the sale contract, desires of the buyer, time to

operate equipment, etc. This delay can be predicted from past experience or the limit for delay can be specified in the contract. This delay creates an accumulation of timber standing, sold, and awaiting harvest. This accumulation is modeled with a level equation designated AS (fig. 52). The removal rate from AS is determined by the delay, called DRT, which is determined by the sales contract or by experience. The rate equation, called RML, is simply the amount of timber sold (AS) divided by the delay in removal (DRT) for each computation time interval (DT).

The amount of seedling habitat, called SE, is the level equation integrated with the amount of timber harvested and the succession rate to the sapling habitat class, called SA. The succession rate from the seedling (SE) to the sapling habitat (SA) is determined by the biological growth rate of the regenerated stand. If plantations of genetically improved seedlings grow faster than natural stands (table 6), the delay is a variable that is

Table 6.--The relation of diameter, age, and expected delay for genetically improved pine plantations established after natural pine stand harvest, Big Pine area, Coastal Plains, North Carolina

Habitat	Median diameter range	Age range	Delay
	Inches	- - - Years - - -	
Seedling	0-1.9	0-5	5
Sapling	2-3.9	6-11	6
Small pulp	4-6.9	12-16	5
Large pulp	7-9.9	17-22	6
Small logs	10-12.9	23-30	8
Mature	13-15.9	31-56	26

changed according to the rate that the natural stands are replaced with plantations of genetically improved seedlings. To keep the first illustration simple, I use constants for the delays. Therefore, the stand succession from one habitat to another is the accumulation for each habitat divided by the delay for each computation time interval (DT).

We now have an operating model consisting of two closed loops--one negative feedback and the other positive feedback. This simple model is familiar to many people in forestry because the basic concept of regulating age class distribution by controlling harvest rate and regeneration is fundamental to forest management. The innovation in this model is the negative feedback loop that provides much better control over the organizational state of the forest than the previous model, which divided the forest area by the desired harvest age to obtain the fraction of area to be harvested each year.

DYNAST-FAM

The equations for the FAM version of the model are listed for the Big Pine inventory (table 5, figs. 52, 53).

An * statement is the first display line and is used to identify the model heading, such as the version of DYNAST. The * appears in the first position followed by one or two spaces and then a heading of less than 50 characters including spaces. Subsequent * statements are treated as NOTE statements.

NOTE statements, subsequent * statements, and statements with the first position blank are used to add information, define variables, identify sectors of the model, and create spaces to make the model listing easy to read.

Each variable can be defined on the same line as the equation. The definition should give the

```
*  DYNAST-FAM
NOTE  BIG PINE FOREST
NOTE
NOTE   MATURE TIMBER LOOP
R  RML.KL=FIFZE(AS.K,(AS.K/DRT),SEL.JK)      REMOVALS (ACRES/YEAR)
L  AS.K=AS.J+DT*(SEL.JK-RML.JK)              ACCUMULATED SALES (AREA)
N  AS=IAS                                    INITIAL ACCUM. SALES (AREA)
R  SEL.KL=SELF.K*FL                          SELL RATE (ACRES/YEAR)
N  FL=TAH/MAX(AMT.ROT)                       FLOW RATE (ACRES/YEAR)
N  AMT=DSE+DSA+DSP+DLP+DSL                       AGE MATURE TIMBER (YEARS)
N  TAH=ISE+ISA+ISP+ILP+ISL+IMT+IAS           TOTAL AREA HABITATS (ACRES)
A  SELF.K=TABHL(TSELF,CV.K,.4,1,.2)          SELL FRACTION (DIM)
T  TSELF=0/.3/.6/1                           TABLE SELL FRACTION
A  CV.K=RSR.K/EQ                             COVERAGE RATIO (DIM)
N  EQ=FL*MAX(ROT-AMT),1)                     EQUILIBRIUM CONSTANT (ACRES)
NOTE
NOTE  STATES OF SUCCESSION
L  SE.K=SE.J+DT*(RML.JK-SSA.JK)          SEEDLING HABITAT (AREA)
N  SE=ISE                                INITIAL SEEDLING HABITAT(AREA)
R  SSA.KL=SE.K/DSE                       SUCCESSION TO SAPLINGS (AREA/YR)
L  SA.K=SA.J+DT*(SSA.JK-SSP.JK)          SAPLING HABITAT (AREA)
N  SA=ISA                                INITIAL SAPLING HABITAT(AREA)
R  SSP.KL=SA.K/DSA                       SUCCESS. TO SMALL PULP (AREA)
L  SP.K=SP.J+DT*(SSP.JK-SLP.JK)           SMALL PULP (AREA)
N  SP=ISP                                INITIAL SMALL PULP (AREA)
P  SLP.KL=SP.K/DSP                       SUCCESS. TO LARGE PULP (AREA/YR)
L  LP.K=LP.J+DT*(SLP.JK-SSL.JK)          LARGE PULP (AREA)
N  LP=ILP                                INITIAL LARGE PULP (AREA)
R  SSL.KL=LP.K/DLP                       SUCC. TO SMALL LOGS (AREA)
L  SL.K=SL.J+DT*(SSL.JK-SRS.JK)          SMALL LOGS (AREA)
N  SL=ISL                                INITIAL SMALL LOGS (AREA)
R  SRS.KL=SL.K/DSL                       SUCC. TO RESERVES (ACRES/YR)
L  RSR.K=RSR.J+DT*(SRS.JK-SEL.JK)        MATURE RESERVES (AREA)
N  RSR=IMT                               INITIAL RESERVES (AREA)
NOTE
NOTE  CONTROLS AND CONSTANTS
SPEC  DT=.25/LENGTH=100                  SPECIFICATIONS
A  PRTPER.K=1+STEP(79,21)                PRINT SPECS.
PRINT  SEL,RML,AS,RSR,SL,LP,SP,SA,SE
A  PLTPER.K=.5+STEP(7.5,20.5)            PLOT SPECS.
PLOT  SE=S,SA=A,SP=P,LP=L,SL=W,RSR=R(0,400)/SEL=*(0,30)
C  ISE=0/ISA=122/ISP=38/ILP=10/ISL=261/IMT=362/IAS=0
NOTE  INITIAL INVENTORY FOR HABITATS (AREA)
C  DSE=8/DSA=7/DSP=5/DLP=6/DSL=8/           DELAYS FOR SUCCESS. (YEARS)
C  DRT=2 YR                              DELAY TIMBER REMOVAL
C  ROT=35                                ROTATION DESIRED (YEARS)
RUN ROTATION 35 YEARS
```

Figure 53.--Equations for DYNAST-FAM.

unit of measure or indicate if the variable is dimensionless. For the FAM version, definitions for the mature-timber loop begin in position 45 and for succession states in position 40. These positions are selected for neatness; however, one or more spaces must be left after the equation.

It is convenient and orderly to begin the equations in position 4. However, the equations may begin in positions from 3 to 7--one or more blanks after the equation type that always appears in position 1. No spaces are permitted within the equations. For most parts of the model, the order of the equations is unimportant. The few exceptions will be noted as the model is developed. Controls and constants are conveniently located at the end of the model, after the first * equation, or any other convenient place.

The SPEC equation can specify four parameters: DT, LENGTH, PRTPER, and PLTPER. For DYNAST it is convenient to use the SPEC equation to assign constants to DT, which is the computation interval, and to LENGTH, which is the number of years the model is to simulate. Because primary interest is in the first 5 to 10 years and then in the 100-year outcome, it is convenient to skip the printing and plotting of output in intermediate periods. This is done by making PRTPER and PLTPER variables with the use of auxiliary equations.

In the FAM version, PRTPER specifications are: Print results every year until time 21, then skip to year 100. This specification can be changed as desired to produce the most useful form of tables.

The PLTPER specifications are: Plot at 0.5-year intervals until time 20.5 and then plot at 8-year intervals. Note that the times used in the STEP function must be related to LENGTH and DT to achieve the desired results. The FAM version asks for plots through year 20, thus the change time is year 20 plus the original plotting interval of 0.5; the STEP constant is the amount desired, 8 years, minus the original plotting interval. The LENGTH is set at 100 to coincide with the PRPTER and PLTPER specifications. For PRTPER and PLTPER intervals of less than 1 year, DT should be between one-half and one-tenth of the shortest print or plot time. This rule is also useful when choosing DT relative to time constants in the model such as DRT.

The PRINT instructions are used to print only those variables that have value for decision and control of the forest. Any variable or constant may be printed and tables may be made very complicated. When adapting the model to a new situation, it is often desirable to print variables such as CV and SELF to find out if the model is actually doing what is intended. It is not necessary to print these variables when the model is iterated for decision and control purposes.

The PLOT instructions may be used to make any number of different plots that use the same or different variables. Each plotted variable must be given a symbol. DYNAMO will scale each variable for plotting or the variables may be scaled as illustrated for the FAM version. Variables to be plotted on the same scale are separated with commas; a slash separates variables plotted on different scales.

Constants such as inventories and delays may be grouped on a card if separated with slashes.

The variable for manipulating the model is the rotation period. A C statement is used to assign ROT, the rotation period desired. This statement may be located any place but is conveniently placed just before RUN, which is the last statement in the model. In the FAM version different rotation periods may be assigned to ROT, one for each run or rerun. However, an RUN statement must always follow each C statement that gives an ROT, and an RUN statement must be the last in the model.

RUN statements are also used to identify the run characteristics. Up to 50 characters, including spaces, may be used one or more spaces after RUN. RUN always begins in location 1. The name of the run is printed on the tables and the plots.

TIME E 00	SEL E 00	RML E 00	AS E 00	RSR E 00	SL E 00	LP E 00	SP E 00	SA E 00	SE E 00
0.00	22.657	0.000	0.000	362.00	261.00	10.00	38.00	122.00	0.00
1.00	22.657	9.376	18.752	370.55	231.84	16.24	46.24	105.57	3.82
2.00	22.657	14.872	29.744	375.68	207.17	22.77	50.92	92.18	14.55
3.00	22.657	18.094	36.187	377.91	186.47	28.96	53.13	82.03	28.32
4.00	22.657	19.982	39.964	377.72	169.18	34.47	53.74	74.95	42.97
5.00	22.657	21.089	42.178	375.51	154.78	39.15	53.45	70.56	57.36
6.00	22.657	21.738	43.476	371.62	142.80	43.02	52.75	68.43	70.91
7.00	22.657	22.118	44.237	366.33	132.81	46.14	52.00	68.15	83.35
8.00	22.657	22.341	44.683	359.86	124.46	48.64	51.43	69.32	94.60
9.00	22.657	22.472	44.944	352.42	117.48	50.66	51.19	71.61	104.69
10.00	22.657	22.549	45.097	344.17	111.63	52.35	51.33	74.74	113.67
11.00	22.657	22.594	45.187	335.23	106.74	53.83	51.90	78.46	121.65
12.00	22.657	22.620	45.240	325.71	102.65	55.22	52.88	82.58	128.71
13.00	22.657	22.635	45.271	315.72	99.28	56.60	54.24	86.94	134.94
14.00	22.657	22.644	45.289	305.34	96.53	58.05	55.93	91.41	140.45
15.00	22.657	22.650	45.299	294.64	94.34	59.61	57.90	95.90	145.31
16.00	22.657	22.653	45.305	283.69	92.67	61.31	60.10	100.34	149.59
17.00	22.657	22.655	45.309	272.56	91.48	63.17	62.47	104.65	153.36
18.00	22.657	22.656	45.311	261.30	90.74	65.20	64.96	108.80	156.69
19.00	22.657	22.656	45.313	249.97	90.41	67.38	67.54	112.77	159.62
20.00	22.657	22.657	45.313	238.61	90.49	69.71	70.15	116.54	162.20
100.00	21.403	21.399	42.798	22.03	171.24	128.54	107.16	149.97	171.26

Figure 54.--A copy of the table produced by the model listed in figure 53. Relate the variables to figures 52 and 53.

As many reruns as desired for one iteration of the model may be made by alternating C statements for ROT with RUN.

In printed outputs the columns are headed with E followed by the positive or negative power of 10 to be multiplied by the number to reconstruct the true value (fig. 54). This scaling permits five significant figures to be printed.

Plots may display one or more scales (fig. 55). The variables associated with each scale are indicated for each plot. When variables coincide at a simulated time, one symbol is plotted and the coincident symbols are printed at the side of the plot.

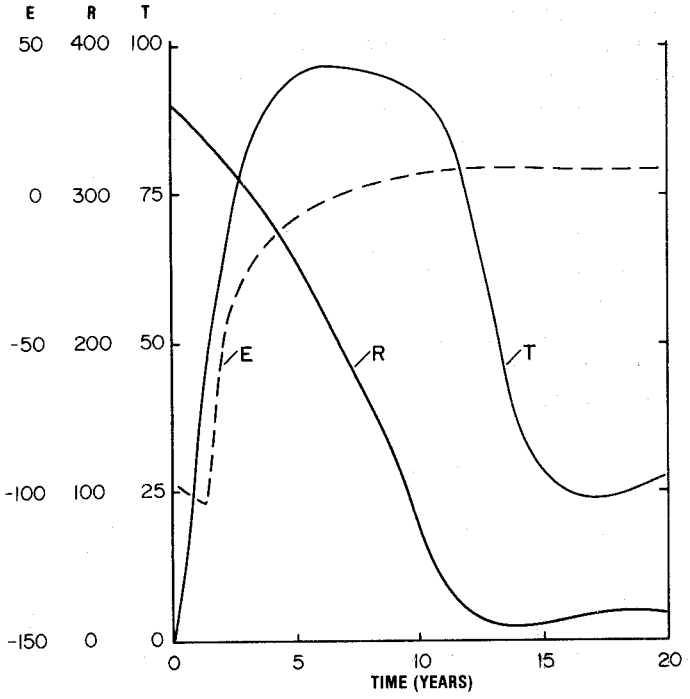

Figure 55.--A modified plot produced by the DYNAST-FAM model.
E = equivalent annual rent in thousands of dollars
R = mature timber reserves, in thousands of acres
T = volume of timber removed, in thousand cubic feet/year
EAR = E, RSR = R, VT = T
Rotation 35 years

Familiar Rotation Results

The preceding version of the model permits harvest simulations only from the mature-timber reserves--stands 35 years and older (table 5). Thus, the shortest rotation that can be simulated is 35 years, but the results of longer rotations can be examined.

Set up a series of reruns that include rotation periods of 35, 45, 55, and 65 years. Examine the prints and plots for similarities and differences. Compare differences in the habitat areas for the ROT options. Consider the differences in timber sale rates for rotation periods. Why does the area of mature reserves increase for a number of years before declining toward the area for steady state? What is the effect of longer rotations on the rate of change in area of seedling habitat? sapling habitat? Why does the area in small logs decline rapidly for all rotation options?

The initial inventory contains adequate areas in the mature and small-log habitats to support timber harvest for rotations of 35 years and longer. Different initial inventories would produce different results. Insert a C statement into the model as follows:

```
C ISE=362/ISA=261/ISP=10/ILP=38/ISL=122/IMT=0/IAS=0
```

The sum of acres in this inventory is 793, the same as for the first illustration (table 5). The difference is that the order of the values is reversed for the habitats. Interpret the results in terms of your knowledge about forestry.

Reruns can be made when both the inventory and the rotation period are changed simultaneously.

Use the original inventory (table 5) and consider the result of planting harvested areas with

genetically improved pines (table 6). For this exercise, change the delay for seedlings, DSE, from 8 to 5 years. Add a STEP equation to reduce the delay for saplings, DSA, from 7 to 6 years at time 12 years.

The above exercises suggest how the delays can be changed to examine the changes in states of organization that may be possible by using fertilizers, drainage controls, and weed controls in plantations.

The results of the preceding exercises have been familiar to foresters for about 200 years. The display of changes in the types by age classes was done years ago with skyline charts after laborious, hand calculations. The sell rates, when mature-timber reserves are adequate, are the amounts found by dividing the forest area by the rotation period (793 acres/35 years = 22.657 acres). The negative feedback loop is permitted to function only when the equilibrium amount, EQ, of mature-timber reserves is less than 1 (fig. 51). This constraint on the negative feedback loop is intentional because I want to illustrate how the DYNAST model is linked to familiar forestry concepts. From this link I will use one or more negative feedback loops to describe how to simulate states of forest organization and the associated benefits in ways that were not available to forest managers before DYNAST.

Use of the Negative Feedback Loop

An important innovation in DYNAST is the use of negative feedback loops to make the development of dynamic plans (ch. 2) a self-organizing operation. Complexity for the planning process is reduced because the managers and other interested parties use only a few control variables to simulate the consequences of alternative strategies. The familiar procedures are structured to aid the decision and control process.

In the model listed in figure 53, values for SELF are limited to a range of 0.4 to 1 by the function TABHL (fig. 51). When the independent variable, CV, exceeds 1, the TABHL function continues to have a value of 1. Thus, if there is a surplus in mature-timber reserves, the timber is not sold any faster than the constant rate determined by dividing the forest area by the rotation period. It is this constraint that gives the familiar results (figs. 54, 55). A more useful structure increases the timber sales when there is a surplus, CV exceeds 1, and reduces sales when there is a shortage, CV is less than 1.

The question is, what rates should be used in the table function for SELF? The range and the waveform for this table determine the behavior of the negative feedback loop and thus direct the timber sale in relation to ROT and the inventory. If the harvest rates are too fast, undesirable oscillations may be initiated in the habitats. If the rates are too slow, mature-timber sales will be unduly delayed. Also, the sell fraction, SELF, must be less than the coverage, CV, or more timber will be scheduled for sale than is available in the mature-timber reserves.

The first step is to establish policies based on knowledge of the behavior of the forest and the desire for achieving a conservative production rate. The range of potential oscillations in the habitats is limited by choosing the policy: Harvest rates will not exceed twice the flow rate for a selected rotation period. This policy sets the limits for the dependent values in the table (TSLF) from 0 to 2. The range of the independent values is limited by choosing the policy: Harvest rates can equal twice the flow rate when the coverage is 0.4 or less. These policies are illustrated as a white box and are made available to all interested parties (fig. 56).

The function TABHL is used because it limits the values for SELF when values for CV are less

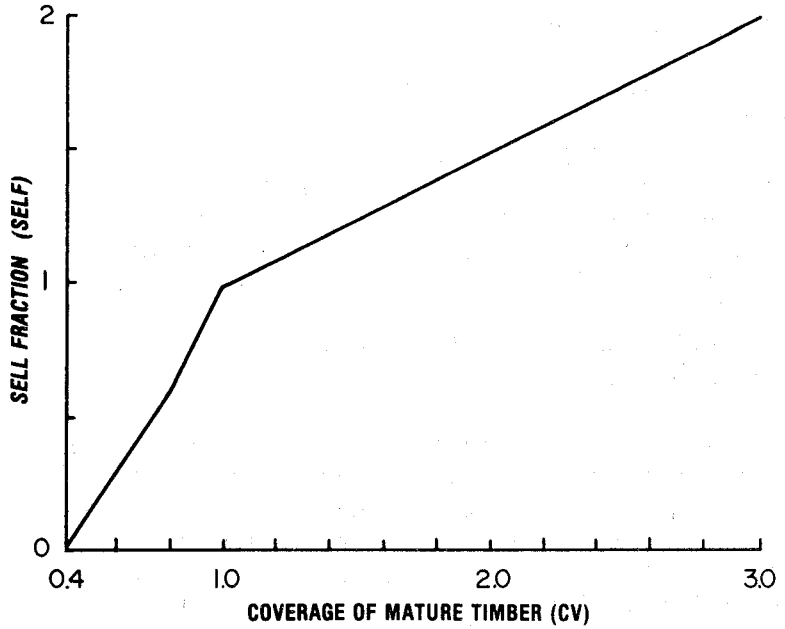

Figure 56.--A white box illustrating policies for selling timber in relation to the coverage of mature timber reserves. CV and SELF are dimensionless.

than 0.4 or greater than 3. When CV is 0.4 or less, SELF is always 0; when CV is 3 or greater, SELF is always 2.

Change the equations for SELF and for TSLF to comply with the new policies (fig. 53). How does this change the behavior of the model?

Consider the oscillations in the habitats and the desirability of the new timber sale rates. Develop different policies based on your perceptions of ecosystem dynamics. How sensitive is the sell fraction, SELF?

Explain how complexity for developing dynamic plans is reduced by establishing policies for the sell fraction and then manipulating only the rotation period.

Succession Rates

The rate equations for succession divide the amount of a habitat by the delay. This is correct if all stands pass through a habitat at the same rate and if there is an equal distribution of age classes in each habitat. If the delays for habitats are short (about one-fifth of the rotation period) and if they are the average time for all stands passing through the habitat, then the errors are small and rarely influence the choice of a strategy.

Accuracy in simulating succession rates can be improved by using a larger number of habitats and by using more complex rate equations. However, this increase in accuracy for the model should be relative to the accuracy that succession can be predicted in the real forest. If the forest is larger than about 200 acres and there are no annual records for all stands, the rate equations can be changed to reflect the more specific information. Such experimentally derived rate equations should be applied cautiously to different areas.

Supplementary Information

Supplementary information is computed and used in prints, plots, and algorithms to estimate the flow of timber, water, wildlife habitat, cash, and other benefits. One of the most useful supplementary items is the proportion of the forest in each habitat by forest type. Changes in these proportions result from timber harvest, succession, forest type conversion, genetically improved seedling use, thinning, fertilizer application, drainage, wildfire, insect attack, disease, and storm damage. For the FAM version of DYNAST add the equations before the sector "controls and constants" (fig. 57). Add a PLOT card to plot these proportions. It is no longer necessary to plot the habitat area.

```
NOTE
NOTE  SUPPLEMENTARY INFORMATION
A   PSE.K=SE.K/TAH                          PERCENT SEEDLINGS
A   PSA.K=SA.K/TAH                          PERCENT SAPLINGS
A   PSP.K=SP.K/TAH                          PERCENT SMALL PULP
A   PLP.K=LP.K/TAH                          PERCENT LARGE PULP
A   PSL.K=SL.K/TAH                          PERCENT SMALL LOGS
A   PMT.K=RSR.K/TAH                         PERCENT MATURE TIMBER
NOTE
```

Figure 57.--Equations for calculating supplementary information.

```
NOTE   POTENTIAL TIMBER INDEX
A   PTI.K=VT.K/TIM                          POTENTIAL TIMBER INDEX
A   VT.K=RML.JK*VU.K*YST                    VOLUME REMOVED (CU. FT.)
A   VU.K=TABXT(TTYI,HAMT.K,0,100,10)        VOLUME UNITS/ACRE
A   HAMT.K=(RSR.K/FL)+AMT                   HARVEST AGE (YEARS)
N   TIM=(TAH/TMR)*TYI*YST                   TIMBER MAXIMUM (CU. FT.)
C   TMR=30                                  ROT FOR MAXIUM TIMBER (YEARS)
N   TYI=TABXT(TTYI,TMR,0,100,10)            VOL. UNITS/ACRE FOR MAX. TIMBER
T   TTYI=0/.3/.68/1/1.22/1.38/1.46/1.49/1.51/1.53/1.55
C   YST=1750                                YIELD STANDARD (CU. FT.)
NOTE
```

Figure 58.--Equations for calculating the potential timber index and the timber volume removed.

Timber Potential

Potential Timber Index

The potential timber index (PTI) is the volume of timber projected for harvest by the DYNAST simulation divided by the volume that would be expected for maximum, sustained timber production (ch. 5). Insert the equations for PTI into DYNAST-FAM (fig. 58).

The expected yields for natural pine stands on the Big Pine forest are given in table 7. Mean annual increment culminates at approximately age 30; the value for TMR is 30. The yield at age 30 is 1,750 cubic feet/acre; YST=1750. This constant is divided into volumes for each class to produce the timber yield indices for the table TTYI. An important advantage to using the indices rather than the

Table 7.--A local yield table and timber yield index for natural pine stands in the Big Pine forest, Coastal Plains, North Carolina

Stand age (years)	Yield[a] (ft^3/acre)	Yield index (vol. units/acre)
10	525	0.3
20	1,190	0.68
30	1,750	1
40	2,135	1.22
50	2,415	1.38
60	2,555	1.46
70	2,605	1.49
80	2,640	1.51
90	2,680	1.53
100	2,715	1.55

[a]Inside bark to a 1-inch top diameter for a site index value of approximately 70 at age 50.

volumes is the ease of changing the yields when the yield tables are harmonic. To change the yield table from site index class 70 to 80, it is only necessary to change the value of the constant for YST. If planting genetically improved seedlings is expected to increase harvested yields in year 25, a STEP function can be used to increase the value of YST at time 25.

The volume that would be expected for maximum sustained timber production is inserted into the model with the N equation for TIM, which is called the timber maximum. The total forest area, TAH, is divided by the age at which mean annual increment, TMR, culminates to give the area for harvest at steady state. This area is then multiplied by the yield standard, YST, and the timber yield index, TYI, to obtain the maximum volume expected.

TYI also is inserted with an N equation. By definition, TYI has a value of 1 when TMR is 30. However, someone may want to use a different TMR to compute PTI. For example, if concern is for saw logs from trees 60 years old rather than for pulpwood from trees 30 years old, the PTI can be adjusted by changing TMR, TTYI, and YST. The value of YST at age 60 is 2,555 (table 7); the C statements are changed to YST=2555, TTYI is changed, and TMR=60. The new potential timber index is now based on producing saw logs rather than pulpwood.

Yield tables can be used for any volume units available. It is only necessary to assure that the values for YST, TMR, and TTYI are appropriate for the scale.

The harvest age is equal to the selected rotation period, ROT, when the forest is at steady state. However, forests are rarely at steady state. Depending on the policy for harvesting, harvest may occur at ages above or below that for ROT. The harvest age is estimated with the auxiliary equation HAMT. By definition, mature-timber reserves (RSR) equals the flow rate multiplied by the time the stands are in the mature-timber habitat. (See the N equation for EQ.) Therefore, dividing RSR by FL gives the number of years of timber supply in the reserves. This number of years is added to the beginning age for the mature-timber habitat to estimate the harvest age. The supposition is that the oldest stands in the reserves will be sold before the younger stands. This simple correction for harvest age is most important when a large area of older stands is in the reserves.

The harvest age of mature timber, HAMT, is used as the independent variable to compute the volume units/acre, VU, for each harvest (table 7). These units are multiplied by the area harvested, RML, and the yield standard, YST, to estimate the volume of timber harvested, VT. This harvested

volume at time K is divided by the maximum potential volume, TIM, to give the potential timber index.

It is useful to plot and to print VT. Change the PLOT statement to simultaneously plot PTI and changes in the habitat proportions. Select a symbol for PTI and scale the plotting from 0 to 2. When can PTI exceed 1?

Add VT to the PRINT statement. Five significant numbers are printed; however, the interpretation and use of these numbers is determined by the validity of the yield table used in the model. Yield tables are estimates of differences and are not intended to be predictions of exact timber volumes. Predictions of harvestable volume are made in-place by measuring merchantable trees before the sale. The PTI and the volume projections made by DYNAST are relative differences for alternative silvicultural modes; they are used to aid decision and control, not to make precise predictions.

Run the version of FAM for some rotation periods from 35 to 100 years. Observe the relation of PTI to the timber volume harvested, the area in reserves, and the changes in the habitat distributions. How does changing the initial inventory affect PTI during the first decade?

Timber and Biomass Volumes

The equations are changed as follows to use yield estimates rather than the timber yield index (table 7):

```
T  TTYI=0/525/1190/1750/2135/2415/2555/2605/2640

X       2680/2715

C       YST=1
```

The timber potential can be changed by making YST the fractional increase or decrease expected for more or less productive sites or by using genetically improved trees. Any units of measure can be used, such as board feet, wet weight, dry weight, or Btu potential.

Variable Rates of Timber Harvest

For some conditions it is desirable to change the timber harvest rates for a planning period of 10 to 20 years. For example, if the initial inventory has a large proportion of accumulated mature timber, it may be desirable to have an initially fast harvest rate and scale the rate downward to smoothly approach the desired rotation period. If the desired rotation period for the Big Pine forest is 45 years, the amount of mature timber at steady state is 176 acres. The inventory of 362 acres of mature timber indicates a surplus of 186 acres that could be rapidly sold in the next few years. The sale of this surplus in 1 year is undesirable for a number of reasons. However, the DYNAST model can be used to scale a variable sales rate that would market the surplus timber during the next 5 years while moving the forest smoothly toward the desired rotation period of 45 years.

Short rotations speed timber sales, and long rotations reduce the sales rate. Thus, a variable sales rate can be scheduled by the DYNAST model by changing the constant ROT, rotation period, to a variable with the table function TABHL. Then for the next 10 or more years of planning, the timber sales rate will follow whatever waveform is put into the table, which I will call TROT. In the mature-timber loop (fig. 53), insert the equation:

```
A       ROT.K=TABHL(TROT,TIME.K,0,10,1)
          Variable rotation (years)
```

One variable rate of timber harvest could be:

```
T       TROT=35/35/36/36/37/38/40/42/44/45/45
```

Tables for TROT are used to change the reruns rather than the constant ROT. However, all constants and initial equations dependent on ROT must be changed to auxiliary equations before the program is run. The following changes are made for the DYNAST-FAM version.

```
R       SEL.KL=SELF.K*FL.K

A       FL.K=TAH/MAX(AMT,ROT.K)

A       CV.K=RSR.K/EQ.K

A       EQ.K=FL.K*MAX((ROT.K-AMT)1)
```

Insert these changes into the model. Draw several waveforms for TROT on graph paper, prepare T and the RUN statements, and examine the results. How do the timber sales rates vary from using the constant ROT=45?

The variable rates are most useful when large areas of old-growth timber are to be converted to a forest with short rotations.

Cash Flows

Net Present Value, NPV

Cash flows are simulated continually as the forest is transformed from state to state. This is accomplished by translating the economic functions into dynamic forms (ch. 6). Insert the equation for cash flow (fig. 59) into DYNAST-FAM.

Net present value at time K is the difference between the present values of the inflows and outflows. Present values are derived by dividing the accumulated inflows and outflows at time K

```
NOTE    CASH FLOW ALGORITHM
A  NPV.K=INAD.K-OTAD.K                    NET PRESENT VALUE ($)
A  INAD.K=INA.K/DSC.K                     INFLOW,SUM DISCOUNTED ($)
L  INA.K=INA.J+DT*(INR.JK)                INFLOW SUMMED ($)
N  INA=IIN                                INITIAL INFLOW SUM ($)
R  INR.KL=(INA.K*(EXP(RIN.K)-1))+IN.K     INFLOW RATE ($/YR)
A  RIN.K=TABXT(TRIN,TIME.K,0,10,1)        REINVESTMENT RATE (DECIMAL)
T  TRIN=.1/.1/.1/.1/.1/.1/.1/.1/.1/.1/.1/   REINVESTMENT TABLE
A  IN.K=NH.K*VYR.K*MOS.K                  TOTAL INFLOW ($)
A  NH.K=VT.K*MA.K                         INFLOW FROM TIMBER ($)
A  MA.K=TABXT(TVAG,HAMT,K,10,100,10)      STUMP PRICE AT HARVEST ($/CU. FT.)
T  TVAG=0/.12/.32/.42/.5/.9/1.1/1.3/1.35/1.4     TABLE STUMP PRICE/AGE
A  VYR.K=TABXT(TVYR,TIME.K,0,20,5)        STUMPAGE PRICE INCREASE
T  TVYR=1/1.1/1.2/1.5/1.7                 TABLE STUMPAGE INCREASE
A  MOS.K=TABHL(TMOS,ASO.K,.1,5.5,.9)      MULTIPLIER FOR OPENING SIZE
T  TMOS=.1/.45/.65/.8/.9/.95/1            MULTIPLIER/SIZE OF OPENING
A  ASO.K=NORMRN(ISO,ISD)                  AVERAGE SIZE OF OPENINGS
A  DSC.K=EXP((MAX(1,TIME.K))*DSR.K)       CONTINUOUS DISCOUNT DIVISOR
A  DSR.K=TABXT(TDSR,TIME.K,0,10,1)        DISCOUNT RATE
T  TDSR=.1/.1/.1/.1/.1/.1/.1/.1/.1/.1/.1    DISCOUNT TABLE
A  OTAD.K=OTA.K/DSC.K                     OUTFLOW, SUM DISCOUNTED ($)
L  OTA.K=OTA.J+DT*(OTR.JK)                OUTFLOW, SUMMED ($)
N  OTA=IOT                                INITIAL OUTFLOW SUM ($)
R  OTR.KL=(OTA.K*(EXP(DSR.K)-1))+OT.K     OUTFLOW RATE ($/YR)
A  OT.K=(OVH.K*TAH)+(MRK.K*SEL.JK)+(IN.K*TXR)    TOTAL OUTFLOW ($)
A  OVH.K=TABXT(TOVH,TIME.K,0,20,5)        OVERHEAD COSTS ($)
T  TOVH=3/3.5/5/6/7                       TABLE OVERHEAD COSTS ($)
A  MRK.K=TABXT(TMRK,TIME.K,0,20,5)        MARKETING COSTS ($)
T  TMRK=8/10/12/15/17                     TABLE MARKETING COSTS ($)
A  PI.K=INAD.K/OTAD.K                     PROFITABILITY INDEX (DIMEN)
A  EAR.K=NPV.K*((DSR.K*DSC.K)/(DSC.K-1))  EQUIVALENT ANNUAL RENT ($/YR)
A  RRR.K=EXP(RR2.K*LOGN(RR1.K))-1         REALIZABLE RATE OF RETURN
A  RR1.K=FIFGE((INA,K/OTAD.K),1,NPV.K,1)          STEP 1 FOR RRR
A  RR2.K=1/(MAX(1,TIME.K))                STEP TWO FOR RRR
C  TXR=.25                               TAX RATE (TAX BRACKET FRACTION)
C  ISO=10/ISD=1              INITIAL SIZE OF OPENING AND VARIANCE
C  IOT=1E5                                INITIAL OUTFLOW DOLLARS
C  IIN=0                                  INITIAL INFLOW DOLLARS
NOTE
```

Figure 59.--Equations for the cash flow algorithm.

by the discount divisor at time K (fig. 45). The inflow and outflow rates are the basic algorithm for continual compounding (fig. 44) with the amounts of inflows (IN) and outflows (OT) added at time K. The most important equations are those that calculate the inflows and the outflows for different silvicultural modes. It is these equations that link silvicultural strategies to cash flows for each forest.

Inflow Equations, IN

Different forests will have different combinations of inflow equations. Those used here and in chapter 6 are for illustration only. Cash inflow at time K is the sum of all funds actually flowing into the organization. Funds may come from the sale of timber and fuelwood, from rights-of-way, hunting rights, leases, water rights, or land sales. For example, the inflows from the mature-timber harvest (NH) are the volume of timber harvested (VT) multiplied by the stumpage value at the time of harvest (MA) (fig. 59). The latter value is taken from a table (TVAG) that is dependent on the harvest age (HAMT) (fig. 58). Plot the table (TVAG) on a piece of graph paper. Change the table if you have information on current stumpage prices for pine in North Carolina.

The perception of changes in stumpage prices (VYR) is from figure 37.

A constraint (MOS) is placed on stumpage values when openings are less than 5.5 acres (fig. 38).

The tax rate is illustrated as a constant (TXR). If tax rate changes, TXR can be written as a table function.

The important consideration is to carefully think through the source for cash inflows, how these may be affected by cultural practices, and how constraints, such as small openings, may affect inflows. The information, insights, and suppositions are expressed in white boxes for scrutiny and revision by all interested parties before equations are written. Table functions are usually the most effective way to put the information into the model.

Outflow Equations, OT

Cash outflow (OT) at time K is the sum of any payment by the organization. These payments may be for overhead costs, taxes, marketing costs, consulting fees, road costs, drainage, site preparation, genetically improved seedlings, fertilizers, sale preparation, supervision, equipment, and structures. Equations for these items are based on white boxes (figs. 39, 40), which are evaluated and challenged by all interested parties before the equations are written. The number of equations can be reduced by aggregating costs that have similar trends.

Exercises

How do cash inflows differ for the perceptions of interest rates illustrated in figures 41, 42, 43?

Make your assumptions about interest rates for the next 10 years visible in white boxes. Insert these assumptions into DYNAST-FAM and examine cash flow for several silvicultural options.

How is cash flow affected by making the reinvestment and discount rates equal? When would these rates be equal? When would the reinvestment rate be less than the discount rate? How do these differences affect cash flows?

For purposes of choosing a silvicultural mode, which of the following changes increase EAR the most in the next decade:

1. Reducing the rotation period from 50 to 35 years or changing the interest rates from those in figure 41 to those in figure 42?

2. Increasing the yield, YST, 10 percent by applying fertilizers to all stands that enter the saw-log class, or reducing the rotation period from 50 to 35 years? The costs for applying the fertilizers is estimated to be $10/acre.

Keep interest rates constant (fig. 41) and find the multipliers for stumpage prices (fig. 37) that are required to make EAR positive in year 30. Assume reforestation is with improved seedlings, planting begins at time 0, the cost is $100/acre, and the cost increases at the rate of 5 percent per year.

If you have current information on pine regeneration costs and expected stumpage values, change the white boxes to fit your information and perceptions. Examine the cash flows for different harvest rates, ROT, and regeneration costs. Find strategies that could be recommended to an investment company for the next 10 years, 35 years, and 70 years. What uncertainties about the future are most likely to change these strategies if the land is not sold and is kept in pine forests?

Opening Size

The average opening size desired for timber harvest is a control variable. The shape and size of openings are influenced by rock outcrops, soil erodibility, streams, springs, bogs, and other conditions that cannot be included in the model. For these reasons the average opening size desired is specified on a C statement as ISO and a limit on the sizes is specified as the initial standard deviation, ISD. This deviation multiplied by 2.4 gives the maximum and the minimum range of opening sizes expected in the implementation. In practice, the in-place decisions are guided by the values assigned to ISO and ISD.

Opening sizes and the variances are modeled with the function NORMRN. The result is an approximate normal distribution in the model, but in the real forest the opening sizes are likely to vary from a normal distribution. The stochastic variance used in DYNAST to model the opening size has value for the decisions primarily as a basis for deciding the limits, ISD, that should be implemented as rules for in-place decisions.

Values for Initial Inflows and Outflows

At time 0, values are assigned on C cards to the initial inflow (IIN) and the initial outflow (IOT). These values may be 0. For the real forest, initial investments may have been or will likely be made to begin a silvicultural mode. These initial investments are inserted as IOT. Receipts at time 0 are less likely than costs, but if there are inflows, they are inserted as IIN.

When changing the silvicultural modes, the initial outflows and inflows should be carefully considered and the constants IOT and IIN estimated as accurately as possible. These initial values are for determining important cash flows.

Modify DYNAST-FAM to consider paying for site preparation equipment, the salary of the operators, depreciation, and operating costs versus contracting for site preparation as needed. Use current cost information. Is the choice different when ROT=35 than when ROT=70?

Plantations, Genetically Improved Trees, and Thinnings

The gains in timber volumes expected from plantations and from the use of genetically improved trees are based on the rapid, early growth of uniformly spaced seedlings. The result is to shorten the delays for transformations from the seedling and sapling habitats and rarely from the older habitats (table 6). When natural stands are being replaced with plantations, the delays may be changed from constants to variables that change according to the conversion rate. A table function is one way to include this change in the model. Another way is to use the STEP function. The equation could be written:

```
A       DSE.K=8+STEP(-3,6)
```

The value of the delay would be 8 years until time 6 when the delay would be reduced to 5 years. For this particular example the shorter delay, 5 years, could be used initially because the inventory is 0 for natural seedling habitats. For this example, it is only necessary to use a STEP function for the sapling habitat. The function would reduce the delay, DSA, from 7 to 6 years at time 12 years. All other delays are the same for plantations as for natural stands (table 6).

Use the original inventory and consider the result of planting harvested areas with genetically improved pines (tables 5, 6). For this exercise, change the delay for seedlings, DSE, from 8 to 5 years. Add a STEP function to reduce the delay for saplings, DSA, from 7 to 6 years at time 12 years (Pugh 1983).

The above exercise suggests how the delays can be altered to examine the changes in the organizational states of a forest that may be possible by using fertilizers, drainage controls, and weed controls in plantations.

Thinnings are simulated as changes in delays without regenerating the stand. The delays may be shortened for transformations to succeeding habitats for two reasons: First, removing trees smaller than the average diameter mechanically increases the average diameter of the residual stand; and second, the residual trees may increase in diameter at a rate faster than the same size trees in unthinned stands. Thinnings may also require changes in the benefit algorithms, such as those for timber yields and wildlife browse (ch. 5).

Simulating a complex forest--one with a number of cover types, conversions, and thinnings--may require a large number of equations. The number of equations is greatly reduced when a series of similar equations can be replaced with a single function. In the DYNAMO notation, such a function is a

MACRO. Each MACRO has an abbreviation that is used in an equation whenever a particular series of computations, previously defined in the model, is to be made. The primary use of MACROs in DYNAST is to provide flexibility and efficiency in adapting the model to multiple forest types and other combinations. Three MACROs are defined: HBTOB for habitats, OBTAH for forest types, and PTISO for timber and openings; definitions for the dummy variables for each of these are given in tables 8, 9, and 10.

HBTOB, the Habitat MACRO

The diagram in figure 49 is expanded in figure 60 to illustrate the transformation of any habitat by natural succession, timber harvest, or both. The series of similar equations for different habitats is written as a MACRO called HBTOB, which is the acronym for "habitat transformation for optimal benefits."

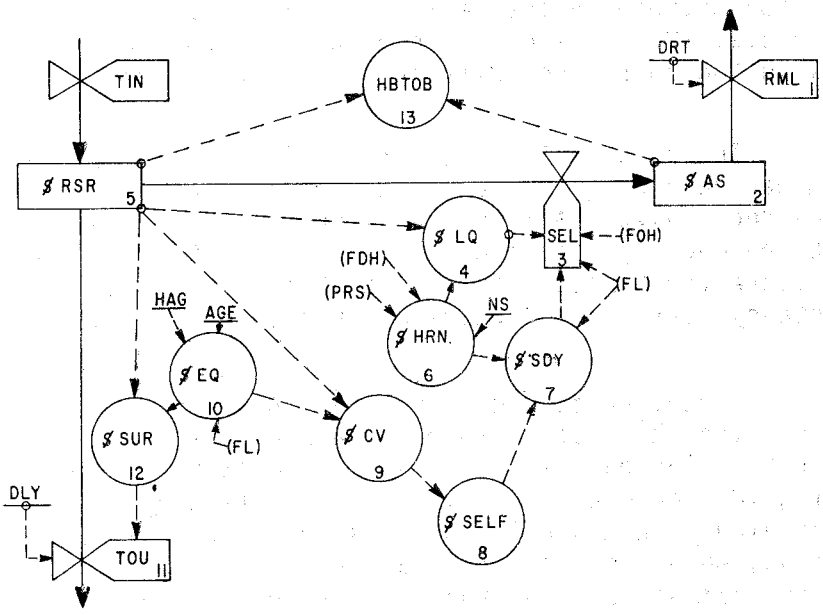

Figure 60.--Diagram of the MACRO HBTOB used to illustrate transformation of a habitat, by natural succession and timber harvest (cf. with fig. 49).

For each habitat (age, type, or size class) the MACRO provides a set of feedback loops that control the harvest rate and the succession rate from this habitat. The harvest and succession rates are regulated by the habitat availability; that is, if the area in a particular habitat is less than the amount required for the desired state of organization, the harvest rate is appropriately delayed on a sliding scale. If the amount of the habitat is more than the desired proportion, its harvest rate is accelerated. Also, a portion of the habitat transforms to the next older class.

The MACRO HBTOB computes changes in the habitat area. The area is the sum of the reserve accumulation of the habitat ($RSR) and the accumulated sales ($AS). The accumulated sales ($AS) are reduced by the amount of habitat removed by harvest (RML) and increased by the sales rate (SEL). The harvest rate is the amount of accumulated sales ($AS) divided by the delay for timber sale and removal (DRT). The latter value is a constant adjusted to reflect differences among contracts.

The amount of habitat to sell (SEL) is determined according to the management mode as specified by the analytic silviculture controls. The choice to be made by the feedback loops is whether to liquidate the habitat ($LQ) or to bring it to the steady state ($SDY) required by the management mode.

A habitat is liquidated when neither it nor any older habitat is to be retained at steady state. The equation for sales rate (SEL) chooses liquidation when no harvest is specified by the silviculture controls for this or older habitats. Thus, when the flow of area for harvest (FL) from the habitat is 0 and the flow of area for all older habitats (FOH) is 0, the function FIFZE chooses a harvest rate ($LQ) that rapidly removes the particular habitat.

The sales rate for liquidating a habitat is limited by the reserve accumulation ($RSR) and the harvest required from the habitat ($HRN). The minimum function (MIN) results in the sale (SEL) eliminating the habitat if the reserve accumulation ($RSR) is smaller than the harvest required ($HRN). Until this final elimination, the sale (SEL) amount is limited by the amount of previous sales from older habitats (PRS).

No harvesting of a younger habitat ($HRN) is required if sales from older habitats (PRS) exceed the total sales permitted from all habitats (FDH). FDH is the amount of harvest needed to create the correct habitat balance in the future, as derived from the controls. When FDH exceeds PRS, the harvest ($HRN) is that required to make up the difference between the sales from the older habitats (PRS) and the total required to bring the habitat distribution to the desired management mode. When no sales are made from older habitats, either the harvest required is limited to $HRN or the habitat is eliminated.

The preceding set of equations is important because it allows older habitats to be smoothly and efficiently liquidated without creating large oscillations in the habitat distribution. Large and continual oscillations, such as could occur without the preceding feedback loops, could more than double the time required to bring the habitat distribution to the desired steady state.

When the age for harvest indicated by the controls is equal to or greater than the age of the habitat being considered, a different set of loops regulates annual sales to bring the habitat to a steady state. The habitat will eventually occupy its appropriate fraction of the forest area, and stands of the designated age will be available for harvest each year at a rate that can be sustained indefinitely ($SDY). This mode operates in cases where FL+FOH is greater than 0.

The first MACRO statement in HBTOB defines a number of inputs (fig. 61). The definition also includes a number of outputs. HBTOB is the total area in the habitat at time K (fig. 60). The variables listed within the parentheses are called dummy arguments. The number and order of the dummies instruct the DYNAMO compiler to substitute a list of variables that are to be identified for a specified habitat for the dummies. The dummies are used only in the definition and are selected to indicate the variables to be identified for specific habitats (Pugh 1983).

Listed first in the parentheses (and defined in table 8) are the input variables TIN through HAG. These occur only on the right-hand side of

```
*  DYNAST-OB, GEORGIA FOREST, 3 TYPES
NOTE
NOTE  STATE OF A HABITAT TYPE (HBTOB)  *DEFINITION*
NOTE
MACRO  HBTOB(TIN,PRS,FL,FOH,FDH,INV,S,DLY,AGE,HAG,TOU,SEL.RML)
R  RML.KL=FIFZE($AS.K,($AS.K/MAX(DRT,1)),SEL.JK)  REMOVALS (AREA/YR)
L  $AS.K=$AS.J+DT*(SEL.JK-RML.JK) ACCUMULATED SALES (AREA)
N  $AS=S       INITIAL ACCUM. SALES (AREA)
R  SEL.KL=FIFZE($LQ.K,$SDY.K,(FL.K+FOH.K))  SELL RATE (AREA/YR)
A  $LQ.K=MIN($RSR.K,$HRN.K)        LIQUIDATE (AREA/YR)
L  $RSR.K=$RSR.J+DT*(TIN.JK-SEL.JK-TOU.JK)  RESERVES (AREA)
N  $RSR=INV         INITIAL INVENTORY FOR RESERVES (AREA)
A  $HRN.K=FIFGE(0,(FDH.K-PRS.K),PRS.K,FDH.K) HARVEST REQUIRED(AREA)
A  $SDY.K=MIN(($SELF.K*FL.K),$HRN.K) STEADY STATE SALES(AREA/YR)
A  $SELF.K=TABHL(TSLF,$CV.K,.4,3,.2)          SELL FRACTION (DIM)
A  $CV.K=$RSR.K/MAX($EQ.K,1E-6)  COVERAGE RESERVES (DIM)
A  $EQ.K=FL.K*MAX((HAG-AGE),1)  EQUILIBRIUM RESERVES(AREA)
R  TOU.KL=FIFZE($SUD.K,$SUF.K,TIN.JK) TRANSFER OUT(AREA/YR)
A  $SUD.K=$SUR.K/$DLS.K  SUCCESSION DECLINE (AREA/YR)
A  $SUR.K=MAX(($RSR.K-$EQ.K),0)  SUCCESSION (AREA)
L  $DLS.K=$DLS.J+DT*($DLI.JK-$DLS.J)  DELAY SUCCESSION (YRS)
N  $DLS=DLY  INITIAL DELAY (YRS)
R  $DLI.KL=FIFZE($DLC.K,DLY,TIN.JK)  DELAY CHANGE(YRS)
A  $DLC.K=MAX(DT,($DLS.K-YR))  DELAY DECLINE (YRS)
A  $SUF.K=($SUR.K/DLY)*$DLM.K  SUCCESSION FLOW (AREA/YR)
A  $DLM.K=TABHL(TDLM,$CHBT.K,0,1,.1)   DELAY MULTIPLIER (DIM)
A  $CHBT.K=$SUR.K/((FOH.K+1)*DLY)  COVERAGE SUCC. RES. (AREA)
A  HBTOB.K=MAX(($RSR.K+$AS.K),0)       HABITAT (AREA)
MEND
T  TSLF=0/.3/.6/1/1.1/1.2/1.3/1.4/1.5/1.6/1.7/1.8/1.9/2   SELL TABLE
T  TDLM=0/0/0/0/.1/.3/.6/.9/.95/.98/1  DELAY MULTIPLE
NOTE
```

Figure 61.--Equations for the MACRO HBTOB, the state of a habitat type.

Table 8.--Definitions for dummy variables used to define MACRO HBTOB

Variable	Definition
	INPUT
TIN	Transfer into this habitat (area/year)
PRS	Previous sales of older habitats (area)
FL	Flow of this habitat (area/year)
FOH	Flow of older habitat (area/year)
FDH	Flow of all habitats (area/year)
INV	Initial inventory (area)
S	Initial accumulated sales (area)
DLY	Delay (years)
AGE	Beginning age for this habitat (years)
HAG	Harvest age desired (years)
	OUTPUT
TOU	Transfer out of this habitat (area/year)
SEL	Sell from this habitat (area/year)
RML	Removals from this habitat (area/year)

equations in the MACRO (fig. 61). The outputs, TOU through RML, are listed after the inputs, are defined by an equation in the MACRO, and may be used in or out of the MACRO to calculate other variables. Variables defined and used only in the MACRO are preceded by $. The MACRO is ended with MEND. Tables and constants can be given values outside of MACROs.

OBTAH, The Forest Type MACRO

The MACRO OBTAH simulates the type transformations which may be defined by forest cover types, soil classes, erodibility classes, productivity

classes, or other criteria. Each type should be defined so that different people can easily recognize and appropriately name the types in-place. Typically, types consist of stands classified by age and area classes. For this version of MACRO OBTAH, specifications are:

- Conversions enter a type as seedlings.
- Reversions leave a type after the timber harvest.
- No harvest or reversions are made from seedling and sapling habitats.

Other kinds of specifications to fit different forest conditions and different silvicultural modes are considered in subsequent sections.

The first MACRO statement in OBTAH (fig. 62) defines a number of inputs and some outputs (table 9). OBTAH is the total area in the type at time K. This area is computed with a level equation that integrates conversions of land, $CON, to the type and reversions of land, RV, from the type. Conversions to the type are inputs to the MACRO. Only conversion to seedlings, CA, is considered. Reversions from the type are outputs. RV is the sum of reversions that result from the harvest of areas from one or more habitats.

The areas reverted, $RC.K--$RG.K, are computed as a function of the area of each habitat harvested at time K. The reversion rates are controlled with the constants CR--GR, which, in the "Analytic Silviculture Controls," are assigned values in the form of decimal fractions. The reversion limit is controlled with the constant RL, which, in the "Analytic Silviculture Controls," is assigned the number of acres desired in this type. The switch function, FIFGE, multiplies area harvested by either the desired reversion rate, CR--GR, or the zero reversion rate.

```
NOTE  STATE OF A FOREST TYPE (OBTAH)     *DEFINITION$
NOTE
MACRO OBTAH (IA,IB,IC,ID,IE,IF,IG,CS,DS,ES,FS,GS,DA,DB,DC,DD,DE,DF,DG,
X  HC,HD,HE,HF,HG,FC,FD,FE,FF,FG,CR,DR,ER,FR,GR,CA,RL,
X  H,RV,SC,SD,SE,SF,SG,CX,DX,EX,FX,GX,GC,GD,GE,GF,GG,A,B,C,D,E,F,G)
L  OBTAH.K=OBTAH.J+DT*($CON.JK-RV.JK)  TYPE (AREA)
N  OBTAH=IA+IB+IC+ID+IE+IF+IG+CS+DS+ES+FS+GS       INITIAL INV. (AREA)
R  $CON.KL=CA.K                CONVERSION RATE (AREA/YR)
R  RV.KL=$RC.K+$RD.K+$RE.K+$RF.K+$RG.K       REVERSION RATE (AREA/YR)
A  $RC.K=CX.JK*FIFGE(CR,0,OBTAH.K,RL)    REVERSION HABITAT C (AREA)
A  $RD.K=DX.JK*FIFGE(DR,0,OBTAH.K,RL)    REVERSION HABITAT D (AREA)
A  $RE.K=EX.JK*FIFGE(ER,0,OBTAH.K,RL)    REVERSION HABITAT E (AREA)
A  $RF.K=FX.JK*FIFGE(FR,0,OBTAH.K,RL)    REVERSION HABITAT F (AREA)
A  $RG.K=GX.JK*FIFGE(GR,0,OBTAH.K,RL)    REVERSION HABITAT G (AREA)
L  A.K=A.J+DT*($TA.JK-$TOA.JK)     HABITAT A (AREA)
N  A=IA                  INVENTORY HABITAT A
R  $TA.KL=MAX((H.K+$TOG.K+CA.K-RV.JK),0)   TRANSFER TO HABITAT A(AREA)
A  H.K=CX.JK+DX.JK+EX.JK+FX.JK+GX.JK      HARVEST TOTAL (AREA)
R  $TOA.KL=A.K/DA                    TRANSFER OUT OF A
L  B.K=B.J+DT*($TOA.JK-$TOB.JK)          HABITAT B (AREA)
N  B=IB                  INVENTORY HABITAT B
R  $TOB.KL=B.K/DB              TRANSFER OUT OF B
A  C.K=HBTOB($TOB.JK,$SDO.K,$FLC.K,$FDO.K,$FCO.K,IC,CS,DC,$AC,HC,
X  $TOC.JK,SC.JK,CX.JK)                  HABITAT C (AREA)
A  D.K=HBTOB($TOC.JK,$SEO.K,$FLD.K,$FEO.K,$FCO.K,ID,DS,DD,$AD,HD,
X  $TOD.JK,SD.JK,DX.JK)                  HABITAT D (AREA)
A  E.K=HBTOB($TOD.JK,$SFO.K,$FLE.K,$FFO.K,$FCO.K,IE,ES,DE,$AE,HE,
X  $TOE.JK,SE.JK,EX.JK)                  HABITAT E (AREA)
A  F.K=HBTOB($TOE.JK,SG.JK,$FLF.K,$FLG.K,$FCO.K,IF,FS,DF,$AF,HF,
X  $TOF.JK,SF.JK,FX.JK)                  HABITAT F (AREA)
A  G.K=HBTOB($TOF.JK,NS,$FLG.K,NS,$FCO.K,IG,GS,DG,$AG,HG,
X  $TOG.JK,SG.JK,GX.JK)                  HABITAT G (AREA)
A  $SDO.K=SD.JK+$SEO.K     SALES HAB. D AND OLDER (AREA)
A  $SEO.K=SE.JK+$SFO.K     SALES HAB. E AND OLDER (AREA)
A  $SFO.K=SF.JK+SG.JK      SALES HAB.F AND OLDER (AREA)
A  $FLC.K=(OBTAH.K*FC)/MAX($AC,HC))   FLOW HABITAT C (AREA/YR)
N  $AC=DA+DB+1      AGE HABITAT C (YR)
A  $FLD.K=(OBTAH.K*FD)/MAX($AD,HD))   FLOW HABITAT D (AREA/YR)
N  $AD=DA+DB+DC+1  AGE HABITAT D (YR)
A  $FLE.K=(OBTAH.K*FE)/(MAX($AE,HE))  FLOW HABITAT E (AREA/YR)
N  $AE=DA+DB+DC+DD+1     AGE HABITAT E (YR)
A  $FLF.K=(OBTAH.K*FF)/(MAX($AF,HF))  FLOW HABITAT F (AREA/YR)
N  $AF=DA+DB+DC+DD+DE+1       AGE HABITAT F (YR)
A  $FLG.K=(OBTAH.K*FG)/(MAX($AG,HG))  FLOW HABITAT G (AREA/YR)
N  $AG=DA+DB+DC+DD+DE+DF+1   AGE HABITAT G (YR)
A  $FCO.K=$FLC.K+$FDO.K       FLOW HAB. C AND OLDER (AREA/YR)
A  $FDO.K=$FLD.K+$FEO.K       FLOW HAB. D AND OLDER (AREA/YR)
A  $FEO.K=$FLE.K+$FFO.K       FLOW HAB. E AND OLDER (AREA/YR)
A  $FFO.K=$FLF.K+$FLG.K       FLOW HAB. F AND OLDER (AREA/YR)
A  GC.K=(C.K/(FIFZE(($TOC.JK+1),($FLC.K+1),HC)))+($AC-1)    HAR AGE C
A  GD.K=(D.K/(FIFZE(($TOC.JK+1),($FLD.K+1),HD)))+($AD-1)    HAR AGE D
A  GE.K=(E.K/(FIFZE(($TOC.JK+1),($FLE.K+1),HE)))+($AE-1)    HAR AGE E
A  GF.K=(F.K/(FIFZE(($TOC.JK+1),($FLF.K+1),HF)))+($AF-1)    HAR AGE F
A  GG.K=(G.K/(FIFZE(($TOC.JK+1),($FLG.K+1),HG)))+($AG-1)    HAR AGE G
MEND
C  NS=0       NULL STANDARD
NOTE
```

Figure 62.--Equations for the MACRO OBTAH, optimal benefits from type and habitat transformations.

Table 9.--Definitions for dummy variables used to define MACRO OBTAH

Variable	Definition
	INPUT
IA--IG	Initial inventories (area)
CS--CG	Initial accumulated sales (area)
DA--DG	Delays (years)
HC--HG	Harvest ages desired (years)
FC--FG	Fractions rotating through habitats (decimal)
CR--GR	Reversion rates desired (decimal)
CA	Conversion to the type (area/year)
RL	Reversion limit (area)
	OUTPUT
H	Total harvested rate (area/year)
RV	Reversion from the type (area/year)
SC--SG	Sell from habitats (area/year)
CX-GX	Removals from habitats (area/year)
GC--GG	Harvest ages (years)
A--G	Area of each habitat (area)

The areas of seedling habitat, A, and sapling habitat, B, are calculated with level equations as in DYNAST-FAM. The transfer rate to seedling habitat, $TA, is the sum of the area harvested, H, natural succession from the oldest habitat, $TOG, and the area converted to the type, CA, corrected for losses due to reversions, RV.

MACRO HBTOB is used to compute the areas of habitats older than the saplings. The input and output variables for each habitat must be specified in the same number and in the order used in the definition (table 9). Some input variables to HBTOB are computed with equations in the MACRO

OBTAH. These computations include the sales and flows of older habitats and the harvest ages. The MACRO is ended with MEND.

PTISO, The Timber and Openings MACRO

The MACRO PTISO uses information from OBTAH to project the timber volumes harvested from a type and from each habitat and the potential timber index for the type. PTISO is the potential timber index for the type and it is computed in the same way as described earlier. From initial values for opening sizes and variances, PTISO computes the annual number of openings and the average opening size.

The first MACRO statement in PTISO (fig. 63) defines a number of inputs and outputs (table 10). Different yield tables are used for the different types. For this version, the format for TABXT is from 0 to 160 years in units of 10 years. If this format is changed, it should be uniform throughout the MACRO PTISO and should agree with the TTYI tables for all types.

Forest Type Sectors

The MACROs are used to simultaneously simulate the transformations of a forest with multiple types, with different silvicultural modes, and with planned or natural type conversions. For each type the appropriate variables are substituted for the dummy variables used in the definitions. Variables are specified only for MACROs OBTAH and PTISO because substitutions are automatically made for the MACRO HBTOB, which is inside the MACRO OBTAH. Appropriate constants and tables are given for each type. The important control variables--such as desired harvest age, fraction rotating through the habitat, reversion rate, reversion limit, and opening size--are located in a convenient place at the end of the model. In this version, this sector is

```
NOTE
NOTE  POTENTIAL TIMBER INDEX, SIZE OF OPENINGS   *DEFINITION*
NOTE
MACRO  PTISO(CX,DX,EX,FX,GX,GC,GD,GE,GF,GG,H,TYPE,TTYI,YST,TMR,ISO,ISD,
X  VT,VC,VD,VE,VF,VG,NO,SO)
A  PTISO.K=VT.K/$TIM.K                    POTENTIAL TIMBER INDEX (DIM)
A  VT.K=VC.K+VD.K+VE.K+VF.K+VG.K          TOTAL VOLUME HARVESTED
A  VC.K=CX.JK*$VUC.K*YST                  VOLUME HABITAT C HARVESTED
A  VD.K=DX.JK*$VUD.K*YST                  VOLUME HABITAT D HARVESTED
A  VE.K=EX.JK*$VUE.K*YST                  VOLUME HABITAT E HARVESTED
A  VF.K=FX.JK*$VUF.K*YST                  VOLUME HABITAT F HARVESTED
A  VG.K=GX.JK*$VUG.K*YST                  VOLUME HABITAT G HARVESTED
A  $VUC.K=TABXT(TTYI,GC.K,0,160,10)       VOLUME UNITS HABITAT C
A  $VUD.K=TABXT(TTYI,GD.K,0,160,10)       VOLUME UNITS HABITAT D
A  $VUE.K=TABXT(TTYI,GE.K,0,160,10)       VOLUME UNITS HABITAT E
A  $VUF.K=TABXT(TTYI,GF.K,0,160,10)       VOLUME UNITS HABITAT F
A  $VUG.K=TABXT(TTYI,GG,K,0,160,10)       VOLUME UNITS HABITAT G
A  $TIM.K=(TYPE.K/TMR)*$TYI*YST            TIMBER MAXIMUM (VOLUME)
N  $TYI=TABXT(TTYI,TMR,0,160,0)           TIMBER YIELD INDEX (VOLUME)
A  SO.K=FIFGE(H.K,(NORMRN(ISO,ISD)),ISO,H.K) SIZE OF OPENING(AREA)
A  NO.K=H.K/MAX(SO.K,.02)                 OPENINGS HARVESTED (NUMBER)
MEND
NOTE
```

Figure 63.--Equations for the MACRO PTISO, potential timber index, and size of opening.

Table 10.--Definitions for dummy variables used to define MACRO PTISO

Variable	Definition
	INPUT
CX--GX	Removals from habitats (area/year)
GC--GG	Harvest ages (years)
H	Total harvest rate (area/year)
TYPE	TYPE from MACRO OBTAH (area)
TTYI	Table, timber volume (units, area)
YST	Yield standard (ft^3)
TMR	Rotation for maximum timber (years)
ISO	Initial opening size (area)
ISD	Initial opening variance (area)
	OUTPUT
VT	Volume of timber removed, total (ft^3)
VC--VG	Timber removed from habitats (ft^3)
NO	Openings harvested/year (number)
SO	Average opening size/year (area)

called "Analytic Silviculture Controls" because these are the controls used to examine the alternative silvicultural modes.

Consider, for example, a forest in central Georgia (tables 11, 12, 13). The stands are classified into three types called pine, oak-pine, and hardwoods. The habitats and the types are transformed by timber harvest, natural succession, timber stand improvements, and regeneration (Boyce and McClure 1975). Transformations may retain the original forest type or convert the stand areas to a different type. The complexity of the transformations is illustrated with a diagram (fig. 64). To keep the illustrations simple, conversions are limited to seedling habitats and harvests are limited to mature habitats.

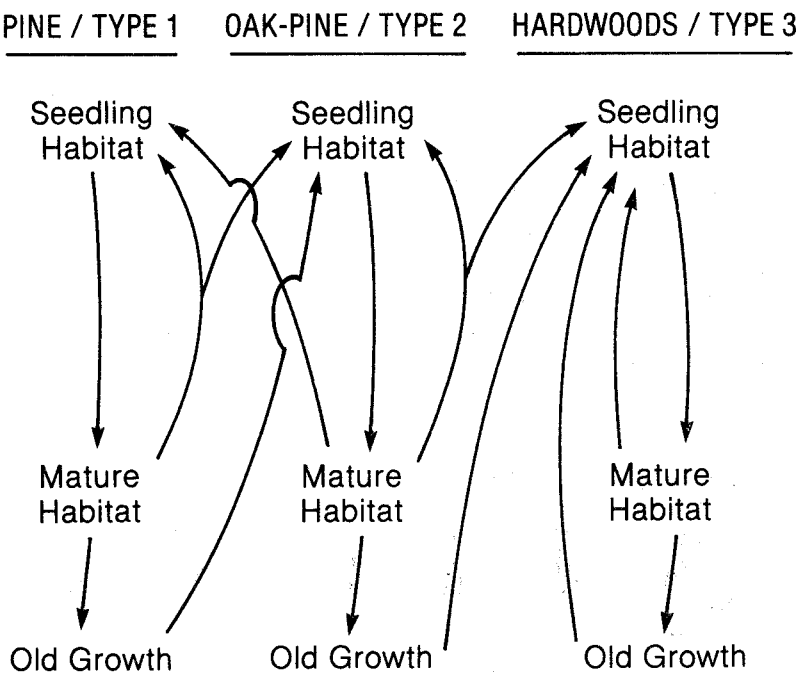

Figure 64.--Diagram illustrating an example of using the MACRO OBTAH to simulate the complex transformations of a forest with conversions among three types (cf. with fig. 52).

Table 11.--TYP1, information for the pine type for a forest in central Georgia

Symbol and habitat	Median diameter range	Age range	Delay	Inventory
	Inches	Years		Acres
A1 seedling	0-1.9	0-8	8	106
B1 sapling	2-3.9	9-15	7	409
C1 small pulp	4-6.9	16-20	5	807
D1 large pulp	7-9.9	21-26	6	902
E1 small logs	10-12.9	27-34	8	504
F1 mature	13-15.9	35-60	26	103
G1 old growth	16+	61-110	50	0
Total			110	2,831

Table 12.--TYP2, information for the oak-pine type for a forest in central Georgia

Symbol and habitat	Median diameter range	Age range	Delay	Inventory
	Inches	Years		Acres
A2 seedlings	0-1	0-5	5	56
B2 sapling	1-4.9	6-30	25	238
C2 pole-6	5-6.9	31-45	15	412
D2 pole-8	7-8.9	46-60	15	210
E2 pole-10	9-10.9	61-75	15	104
F2 mature	11-15.9	6-110	35	96
G2 old growth	16+	111-300	190	0
Total			300	1,116

Table 13.--TYP3, information for the hardwood type for a forest in central Georgia

Symbol and habitat	Median diameter range	Age range	Delay	Inventory
	Inches	Years		Acres
A3 seedlings	0-1	0-5	5	209
B3 saplings	1-4.9	6-35	30	396
C3 pole-6	5-6.9	36-50	15	584
D3 pole-8	7-8.9	51-65	15	214
E3 pole-10	9-10.9	66-85	15	105
F3 mature	11-15.9	86-120	40	781
G3 old growth	16+	121-300	180	156
Total			300	2,445

When mature pine stands are harvested, some of the areas are regenerated back to pine and some to oak-pine. When oak-pine stands are harvested, some areas are regenerated to pine, some to oak-pine, and some to hardwoods. Harvested hardwood areas tend to regenerate to hardwoods unless some cultural practice is used to regenerate them to pine. Many combinations of conversion rates are possible and each has a different flow of timber, cash, wildlife habitats, and other benefits. The MACRO OBTAH makes it possible to simulate these transformations for different silvicultural options.

The structure of the MACRO OBTAH is essentially the same as the core model for DYNAST (fig. 52). Negative feedback loops have the goal of bringing about and maintaining the state of forest organization that provides the desired optimal combination of benefits. Harvest can be from any habitat and simultaneously from any combination of habitats.

The Georgia pine forest is used to illustrate how the model is adapted to a forest. First, the essential information is obtained for the three forest types (tables 11, 12, 13). For the MACRO HBTOB, the pine type is designated TYP1, the oak-pine type TYP2, and the hardwood type TYP3 (fig. 65). Variables designated to be substituted into the MACROs are identified by appending a number, such as 1, 2, or 3, to agree with the type designation. Appropriate constants and tables are given values.

Ten or more types could be used, but decisions and controls are less complex when the number of types is kept to five or less. For more than three types, the option jumbo, J, for the DYNAMO compiler should be used because the number of equations can exceed 1,000 (Pugh 1983).

```
NOTE        ***********<FOREST TYPE SECTOR<*************
NOTE
NOTE  FOREST TYPE 1 **GEORGIA PINE TYPE***
A   TYP1.K=OBTAH(IA1,IB1,IC1,ID1,IE1,IF1,IG1,
X   CS1,DS1,ES1,FS1,GS1,
X   DA1,DB1,DC1,DD1,DE1,DF1,DG1,
X   HC1,HD1,HE1,HF1,HG1,
X   FC1,FD1,FE1,FF1,FG1,
X   CR1,DR1,ER1,FR1,GR1,
X   CA1.K,RL1,H1.K,RV1.JK,
X   SC1.K,SD1.K,SE1.K,SF1.K,SG1.K,
X   CX1.JK,DX1.JK,EX1.JK,FX1.JK,GX1.JK,
X   GC1.K,GD1.K,GE1.K,GF1.K,GG1.K,
X   A1.K,B1.K,C1.K,D1.K,E1.K,F1.K,G1.K)
NOTE
NOTE  TIMBER AND OPENINGS   TYPE 1 **GEORGIA PINE TYPE**
NOTE
A   PTI.K=PTISO(CX1.JK,DX1.JK,EX1.JK,FX1.JK,GX1.JK,
X   GC1.K,GD1.K,GE1.K,GF1.K,GG1.K,H1.K,TYP1.K,TTY1,YST1,TMR1,ISO1,ISD1,
X   VT1.K,VC1.K,VD1.K,VE1.K,VF1.K,VG1.K,NO1.K,SO1.K)
C   IA1=106/IB1=409/IC1=807/ID1=902/IE1=504/IF1=103/IG1=0
C   CS1=0/DS1=0/ES1=0/FS1=0/GS1=0
C   DA1=8/DB1=7/DC1=5/DD1=6/DE1=8/DF1=26/DG1=50
C   YST1=1750/TMR1=30
T   TTY1=0/.3/.68/1/1.22/1.38/1.46/1.49/1.51/1.53/1.55/
X   1.57/1.58/1.59/1.6/1.6/1.6
```

Continued

Continued

```
NOTE
NOTE  FOREST TYPE 2 **GEORGIA OAK-PINE TYPE**
NOTE
A  TYP2.K=OBTAH(IA2,IB2,IC2,ID2,IE2,IF2,IG2,
X  CS2,DS2,ES2,FS2,GS2,
X  DA2,DB2,DC2,DD2,DE2,DF2,DG2,
X  HC2,HD2,HE2,HF2,HG2,
X  FC2,FD2,FE2,FF2,FG2,
X  CR2,DR2,ER2,FR2,GR2,
X  CA2.K,RL2,H2.K,RV2.JK,
X  SC2.K,SD2.K,SE2.K,SF2.K,SG2.K,
X  CX2.JK,DX2.JK,EX2.JK,FX2.JK,GX2.JK,
X  GC2.K,GD2.K,GE2.K,GF2.K,GG2.K,
X  A2.K,B2.K,C2.K,D2.K,E2.K,F2.K,G2.K)
NOTE
NOTE  TIMBER AND OPENINGS  TYPE 2 **GEORGIA OAK-PINE TYPE**
NOTE
A  PT2.K=PTISO(CX2.JK,DX2.JK,EX2.JK,FX2.JK,GX2.JK,
X  GC2.K,GD2.K,GE2.K,GF2.K,GG2.K,H2.K,TYP2.K,TTY2,YST2,TMR2,ISO2,ISD2,
X  VT2.K,VC2.K,VD2.K,VE2.K,VF2.K,VG2.K,NO2.K,SO2.K)
C  IA2=56/IB2=238/IC2=412/ID2=210/IE2=104/IF2=96/IG2=0
C  CS2=0/DS2=0/ES2=0/FS2=0/GS2=0
C  DA2=5/DB2=25/DC2=15/DD2=15/DE2=15/DF2=35/DG2=190
C  YST2=2680/TMR2=50
T  TTY2=0/.25/.45/.6/.81/1/1.18/1.33/1.47/1.61/1.75/1.85/1.89/1.92/
X  1.94/1.96/1.97
NOTE


NOTE
NOTE  FOREST TYPE 3 **GEORGIA HARDWOOD TYPE**
NOTE
A  TYP3.K=OBTAH(IA3,IB3,IC3,ID3,IE3,IF3,IG3,
X  CS3,DS3,ES3,FS3,GS3,
X  DA3,DB3,DC3,DD3,DE3,DF3,DG3,
X  HC3,HD3,HE3,HF3,HG3,
X  FC3,FD3,FE3,FF3,FG3,
X  CR3,DR3,ER3,FR3,GR3,
X  CA3.K,RL3,H3.K,RV3.JK,
X  SC3.K,SD3.K,SE3.K,SF3.K,SG3.K,
X  CX3.JK,DX3.JK,EX3.JK,FX3.JK,GX3.JK,
X  GC3.K,GD3.K,GE3.K,GF3.K,GG3.K,
X  A3.K,B3.K,C3.K,D3.K,E3.K,F3.K,G3.K)
NOTE
NOTE  TIMBER AND OPENINGS  TYPE 3 **GEORGIA HARDWOOD TYPE**
NOTE
A  PT3.K=PTISO(CX3.JK,DX3.JK,EX3.JK,FX3.JK,GX3.JK,
X  GC3.K,GD3.K,GE3.K,GF3.K,GG3.K,H3,K,TYP3.K,TTY3,YST3,TMR3,ISO3,ISD3,
X  VT3.K,VC3.K,VD3.K,VE3.K,VF3.K,VG3.K,NO3.K,SO3.K)
C  IA3=209/IB3=396/IC3=584/ID3=214/IE3=105/IF3=781/IG3=156
C  CS3=0/DS3=0/ES3=0/FS3=0/GS3=0
C  DA3=5/DB3=30/DC3=15/DD3=15/DE3=15/DF3=40/DG3=180
C  YST3=2680/TMR3=50
T  TTY3=0/.23/.41/.6/.81/1/1.18/1.33/1.47/1.61/1.75/1.85/1.89/1.92/
X  1.94/1.96/1.97
NOTE
```

Figure 65.--Equations for the forest type sectors for a pine forest in central Georgia.

Supplementary Information

This part of the model is expanded to calculate information needed for printing and plotting. The order of the equations is not important and equations can be added and removed as the model is manipulated. If conversions are desired or if they occur naturally (Boyce and McClure 1975), equations for designating these transformations may be located in this sector. This sector is also a convenient place to calculate variables used in more than one algorithm for benefits and impacts. Examples of supplementary equations are given in figure 66.

Benefit and Impact Information

This sector includes the algorithms for whatever benefits and effects are to be examined. The techniques for developing algorithms are described in chapter 5. The algorithms may be inserted and removed at will without affecting transformations in the state of forest organization. An example is the habitat for deer (fig. 67).

```
NOTE
NOTE  SUPPLEMENTARY INFORMATION
NOTE
A  CA1.K=(RV2.JK*CT21)+(RV3.JK*CT31)     CONVERT TO TYP1 (AREA)
A  CA2.K=(RV1.JK*CT12)+(RV3.JK*CT32)     CONVERT TO TYP2 (AREA)
A  CA3.K=(RV1.JK*CT13)+(RV2.JK*CT23)     CONVERT TO TYP3 (AREA)
A  PP1.K=TYP1.K/TAH.K            PERCENT PINE TYPE
A  TAH.K=TYP1.K+TYP2.K+TYP3.K        TOTAL AREA HABITATS
A  PP2.K=TYP2.K/TAH.K            PERCENT OAK-PINE TYPE
A  PP3.K=TYP3.K/TAH.K          PERCENT HARDWOOD TYPE
A  PSE.K=(A1.K+A2.K+A3.K/TAH.K          SEEDLING HABITAT (%)
A  OPM.K=TNO.K/(TAH.K/640)     OPENINGS PER SQ. MILE/YR
A  TNO.K=NO1.K+NO2.K+NO3.K        TOTAL OPENINGS (NUMBER)
A  ASO.K=TH.K/MAX(TNO.K,1)     AVERAGE SIZE OF OPENINGS (AREA)
A  TH.K=H1.K+H2.K+H3.K               TOTAL HARVEST (AREA)
* >>>>>>>>>> HARD MAST <<<<
A  HM.K=HMI.K*HMD.K            HARD MAST POTENTIAL
A  HMI.K=TABHL(THMI,PHMO.K,0,.7,.1)     HARD MAST INCREASE INDEX
A  PHMO.K=(F2.K+G2.K+F3.K+G3.K)/TAH.K     HARD MAST HABITATS (%)
T  THMI=.1/.3/.5/.7/.8/.9/.95/1          HARD MAST INCREASE TABLE
A  HMD.K=TABHL(THMD,POG,K,0,.7,.1)       HARD MAST DECREASE INDEX
A  POG.K=(G2.K+G3.K)/TAH.K          OLD HARD MAST HABITATS (%)
T  THMD=1/1/.98/.95/.9/.85/.8/.75    HARD MAST DECREASE TABLE
NOTE
```

Figure 66.--Equations for supplementary information.

```
NOTE  ***BENEFIT AND IMPACT EQUATIONS****
NOTE
* >>>>>>>>> DEER <<<<
NOTE
A  DEER.K=HTD.K*OTD.K*HMDE.K          DEER HABITAT POTENTIAL
A  HTD.K=TABHL(THTD,PSE.K,0,.07,.01)   BROWSE POTEN. FOR DEER
T  THTD=.1/.2/.4/.7/.9/.95/.98/1        TABLE BROWSE POTEN.
A  OTD.K=TABXT(TOTD,OPM.K,0,.5,.1)     OPENING DISPERSION FOR DEER
T  TOTD=.2/.4/.7/.9/.95/1  TABLE OF DEER OPENING DISPERSAL
A  HMDE.K=TABHL(THMDE,HM.K,0,.5,.1)  HARD MAST FOR DEER POTEN.
T  THMDE=.3/.4/.6/.8/1/1          TABLE HARD MAST FOR DEER
NOTE
```

Figure 67.--Equations for benefit and impact information.

The benefit equations are structurally independent of the core equations except that they use the output of the core model. The benefits depend directly on the organizational state. Thus, computing benefits is a matter of relating each benefit to the state of the forest or to the proportion of habitats. Once these relations or algorithms are determined by research and experience, benefits can be projected in relation to changes in the state of the forest.

Following are several important points about the benefit and impact equations:

1. The core equations are not dependent on any of the benefit equations.

2. Benefit equations can be added, modified, or removed from the DYNAST model without affecting any of the other benefit algorithms and without affecting the core equations.

3. Algorithms can be written for any benefit and impact that can be related to the organizational state of the forest. The important variables are the distribution of forest stands within forest types by

age and area classes, the timber harvest rates, and the size of opening formed by timber harvest.

4. The management modes determine the organizational states, which, in turn, determine the combinations of benefits and impacts.

Cash Flow Algorithm

The cash flow algorithm is included or excluded at will. When used, the cash inflow and outflow equations must be modified to reflect the multiple forest types, regeneration costs, conversion costs, timber sales, and sale of hunting and recreation rights (fig. 68).

Program Controls Sector

This sector is used to give the specifications for DT, LENGTH, PRINT, and PLOT. Once these controls are selected for a particular forest, few changes are needed when different silvicultural strategies are being evaluated (fig. 69).

Analytic Silviculture Controls

This sector contains the controls used to change the silvicultural mode; it is the set of control variables in the decision loop (fig. 3). The first run is called ZERO because all variables are set at zero or at natural transformation rates. In the reruns, concern is with the variables that identify a silvicultural mode rather than with manipulating all of the constants. Both constants and tables may be changed in the reruns. When C and T statements are used in reruns, the constants and tables revert to the values in the ZERO run. RUN must be the last statement in each rerun (fig. 69).

```
NOTE
NOTE     CASH FLOW ALGORITHM
NOTE
A  NPV.K=INAD.K-OTAD.K                    NET PRESENT VALUE ($)
A  INAD.K=INA.K/DSC.K                     INFLOW,SUM DISCOUNTED ($)
L  INA.K=INA.J+DT*(INR.JK)                INFLOW SUMMED ($)
N  INA=IIN                                INITIAL INFLOW SUM ($)
R  INR.KL=(INA.K*(EXP(RIN.K)-1))+IN.K     INFLOW RATE ($/YR)
A  RIN.K=TABXT(TRIN,TIME.K,0,10,1)        REINVESTMENT RATE (DECIMAL)
T  TRIN=.1/.1/.1/.1/.1/.1/.1/.1/.1/.1/.1/   REINVESTMENT TABLE
A  IN.K=NH.K*VYR.K*MOS.K                  TOTAL INFLOW ($)
A  NH.K=NC1.K+ND1.K+NE1.K+NF1.K+NG1.K+NC2.K+ND2.K+NE2.K+NF2.K+NG2.K+
X  NC3.K+ND3.K+NE3.K+NF3.K+NG3.K          TOTAL DOLLARS FOR TIM.
A  NC1.K=VC1.K*(TABXT(TVA1,GC1.K,10,100,10))       DOLLARS FOR TIM
T  TVA1=0/.12/.32/.42/.5/.9/1.1/1.3/1.35/1.4      PINE STUMP PRICE/AGE
A  ND1.K=VD1.K*(TABXT(TVA1,GD1.K,10,100,10))       DOLLARS FOR TIM
A  NE1.K=VE1.K*(TABXT(TVA1,GE1.K,10,100,10))       DOLLARS FOR TIM
A  NF1.K=VF1.K*(TABXT(TVA1,GF1.K,10,100,10))       DOLLARS FOR TIM
A  NG1.K=VG1.K*(TABXT(TVA1,GG1.K,10,100,10))       DOLLARS FOR TIM
A  NC2.K=VC2.K*(TABXT(TVA2,GC2.K,0,160,20))        DOLLARS FOR TIM
T  TVA2=0/.04/.08/.12/.3/.32/.34/.44/.5     HARDWOOD STUMP PRICE
A  ND2.K=VD2.K*(TABXT(TVA2.GD2.K,0,160,20))        DOLLARS FOR TIM
A  NE2.K=VE2.K*(TABXT(TVA2.GE2.K,0,160,20))        DOLLARS FOR TIM
A  NF2.K=VF2.K*(TABXT(TVA2.GF2.K,0,160,20))        DOLLARS FOR TIM
A  NG2.K=VG2.K*(TABXT(TVA2.GG2.K,0,160,20))        DOLLARS FOR TIM
A  NC3.K=VC3.K*(TABXT(TVA2.GC3.K,0,160,20))        DOLLARS FOR TIM
A  ND3.K=VD3.K*(TABXT(TVA2.GD3.K,0,160,20))        DOLLARS FOR TIM
A  NE3.K=VE3.K*(TABXT(TVA2.GE3.K,0,160,20))        DOLLARS FOR TIM
A  NF3.K=VF3.K*(TABXT(TVA2.GF3.K,0,160,20))        DOLLARS FOR TIM
A  NG3.K=VG3.K*(TABXT(TVA2.GG3.K,0,160,20))        DOLLARS FOR TIM
A  VYR.K=TABXT(TVYR,TIME.K,0,20,5)        STUMPAGE PRICE INCREASE
T  TVYR=1/1.1/1.2/1.5/1.7                 TABLE STUMPAGE INCREASE
A  MOS.K=TABHL (TMOS,ASO.K,.1,5.5,.9)     MULTIPLIER FOR OPENING SIZE
T  TMOS=.1/.45/.65/.8/.9/.95/1            MULTIPLIER/SIZE OF OPENING
A  DSC.K=EXP((MAX(1,TIME.K))*DSR.K)       CONTINUOUS DISCOUNT DIVISOR
A  DSR.K=TABXT(TDSR,TIME.K,0,10,1)        DISCOUNT RATE
T  TDSR=.1/.1/.1/.1/.1/.1/.1/.1/.1/.1/.1    DISCOUNT TABLE
A  OTAD.K=OTA.K/DSC.K                     OUTFLOW, SUM DISCOUNTED ($)
L  OTA.K=OTA.J+DT*(OTR.JK)                OUTFLOW, SUMMED ($)
N  OTA=IOT                                INITIAL OUTFLOW SUM ($)
R  OTR.KL=(OTA.K*(EXP(DSR.K)-1))+OT.K     OUTFLOW RATE ($/YR)
A  OT.K=(OVH.K*TAH.K)+(MRK.K*TH.K)+(IN.K*TXR)        TOTAL OUTFLOW ($)
A  OVH.K=TABXT(TOVH,TIME.K,0,20,5)        OVERHEAD COSTS ($)
T  TOVH=3/3.5/5/6/7                       TABLE OVERHEAD COSTS ($)
A  MRK.K=TABXT(TMRK,TIME.K,0,20,5)        MARKETING COSTS ($)
T  TMRK=8/10/12/15/17                     TABLE MARKETING COSTS ($)
A  PI.K=INAD.K/MAX(OTAD.K,1)              PROFITABILITY INDEX (DIM)
A  EAR.K=NPV.K*((DSR.K*DSC.K)/(DSC.K-1))   EQUIVALENT ANNUAL RENT ($/YR)
A  RRR.K=EXP(RR2.K*LOGN(RR1.K))-1         REALIZABLE RATE OF RETURN
A  RR1.K=FIFGE((INA.K/MAX(OTAD.K,1)),1,NPV.K,1)     STEP 1 FOR RRR
A  RR2.K=1/(MAX(1,TIME.K))                STEP TWO FOR RRR
C  TXR=.25                               TAX RATE (TAX BRACKET FRACTION)
NOTE
```

Figure 68.--Equations for cash flow for three forest types.

```
NOTE  PROGRAM CONTROLS SECTOR
NOTE
SPEC  DT=.25/LENGTH=100
A  PRTPER.K=1+STEP(79,21)
PRINT 1)SC1,SD1/2)SE1,SF1/3)SG1,SC2/4)SD2,SE2/5)SF2,SG2/6)SC3,SD3/
X  7)SE3,SF3/8)SG3,VT1/9)VT2,VT3/10)TH,OPM/11)TNO,ASO/12)HM,HTD/
X  13)NPV,PI/14)EAR,RRR
A  PLTPER.K=.5+STEP(7.5,20.5)
PLOT  PT1=1,PT2=2,PT3=3(0,2)/PP1=P,PP2=0,PP3=H,DEER=D(0,1)
NOTE
NOTE  **ANALYTIC SILVICULTURE CONTROL***
C  DRT=0                    DELAY TIMBER REMOVAL (YR)
C  IIN=0/IOT=0              INITIAL INFLOW AND OUTFLOW OF CASH($)
C  CT12=0/CT13=0      TYP1 TO TYP2 AND TYP3 (DECIMAL)
C  CT21=0/CT23=0      TYP2 TO TYP1 AND TYP3 (DECIMAL)
C  CT31=0/CT32=0      TYP3 TO TYP1 AND TYP2 (DECIMAL)
C  RL1=0/RL2=0/RL3=0          REVERSION LIMITS (AREA)
C  ISO1=0/ISO2=0/ISO3=0     DESIRED OPENING SIZE (AREA)
C  ISD1=0/ISD2=0/ISD3=0      DESIRED OPENING DEVIATION (AREA)
C  HC1=0/HD1=0/HE1=0/HF1=0/HG1=0       HARVEST AGE DESIRED (YR)
C  HC2=0/HD2=0/HE2=0/HF2=0/HG2=0       HARVEST AGE DESIRED (YR)
C  HC3=0/HD3=0/HE3=0/HF3=0/HG3=0       HARVEST AGE DESIRED (YR)
C  FC1=0/FD1=0/FE1=0/FF1=0/FG1=0       FRACTIONS ROTATING (DECIMAL)
C  FC2=0/FD2=0/FE2=0/FF2=0/FG2=0       FRACTIONS ROTATING (DECIMAL)
C  FC3=0/FD3=0/FE3=0/FF3=0/FG3=0       FRACTIONS ROTATING (DECIMAL)
C  CR1=0/DR1=0/ER1=0/FR1=0/GR1=0       REVERSION RATES (DECIMAL)
C  CR2=0/DR2=0/ER2=0/FR2=0/GR2=0       REVERSION RATES (DECIMAL)
C  CR3=0/DR3=0/ER3=0/FR3=0/GR3=0       REVERSION RATES (DECIMAL)
RUN ZERO
C  HE1=30/FE1=.3/HF1=45/FF1=.7/ISO1=30/ISD1=2
C  HD2=50/FD2=1/ISO2=30/ISD2=2
C  HE3=80/FE3=.8/HG3=260/FG3=.2/ISO3=10/ISD3=1
RUN OPTION 1
C  HE1=30/FE1=.3/HF1=45/FF1=.7/ISO1=30/ISD1=2
C  HD2=50/FD2=1/ISO2=30/ISD2=2
C  HE3=80/FE3=.8/HG3=260/FG3=.2/ISO3=10/ISD3=1
C  CR1=.54/DR1=.54/ER1=.54/FR1=.54/GR1=.54
C  CR2=.73/DR2=.73/ER2=.73/FR2=.73/GR2=.73
C  CR3=.16/DR3=.16/ER3=.16/FR3=.16/GR3=.16
C  CT12=.68/CT13=.32/CT21=.26/CT23=.74/CT31=.12/CT32=.88
RUN   OPTION 2
```

Figure 69.--Equations for the program and the analytic silviculture controls.

Sequence of the Sectors

The constraint is that user-defined MACROs must be defined before being used. The important sequence is to define MACRO HBTOB, MACRO OBTAH, and MACRO PTISO in this order. The other sectors may be in any desired sequence. The sectors are described in a convenient order. The first display line in the model should be an * statement to

identify the version of DYNAST and the forest; the last should be an RUN statement.

Exercises Without Type Conversion

Thirty percent of the pine type is to be harvested at age 30; 70 percent is to be harvested at age 45. The desired opening size is 30 ± 5 acres. The controls are:

```
C  HE1=30/FE1=.3/HF1=45/FF1=.7/ISO1=30/ISD1=2
```

All of the oak-pine type is to be harvested at age 50 with openings 30 ± 5 acres. The controls are:

```
C  HD2=50/FD2=1/ISO2=30/ISD2=2
```

Eighty percent of the hardwood type is to be harvested at age 80 and 20 percent at age 260. Openings are to be 10 ± 2.5 acres. The controls are:

```
C  HE3=80/FE3=.8/HG3=260/FG3=/.2/ISO3=10/ISD3=1
```

The desired variance for opening size must be divided by 2.4 because of the function NORMRN (Pugh 1983). Run this option. What are the expected benefits for the next 10 years?

What are the benefits expected when 90 acres of mature pine are initially sold, FS1=90; 200 acres of oak-pine, pole 8, are initially sold, DS2=200; and 700 acres of mature hardwoods are initially sold, FS3=700?

What are the benefits of delaying the contract for removals, DRT, from 2 to 5 years?

Develop three strategies to present to your organization; include a statement of organizational goals and exclude type conversions.

Forest Type Reversions and Conversions

Reversions from and conversions to forest types change the organizational state of the forest and the availability of benefits. Both natural and cultural forces change the forest type area. Between 1961 and 1972, pine and hardwood forest land, cropland, and urban land in Georgia were converted and reverted (Boyce and McClure 1975). How these kinds of transformations affect the availability of forest benefits can be simulated with the DYNAST model. For illustration, I use the three forest types previously described.

Following natural mortality and harvesting without cultural practices to direct regeneration, the reversion rate from pine is approximately 0.54, that from oak-pine is 0.74, and that from hardwoods is 0.16. These proportions of the areas harvested are removed from the original type and converted to a different land use. The actual land area reverted at time K is the area harvested or cleared by natural mortality multiplied by the reversion rate. Thus, the amounts of area reverted are a function of harvest and mortality which create openings for regeneration in mature and old-growth stands.

The reversion rates are inserted into the model as values for CR--GR (fig. 69). The same rates are used for all age classes because there is no evidence for differences among the habitats. The analytic silviculture controls for reversion rates are written:

```
C    CR1=.54/DR1=.54/ER1=.54/FR1=.54/GR1=.54

C    CR2=.74/DR2=.74/ER2=.74/FR2=.74/GR2=.74

C    CR3=.16/DR3=.16/ER3=.16/FR3=.16/GR3=.16
```

For this example, the areas reverted from one type may be converted to the other two types at

Table 14.--Definitions of quantity names for conversions, and quantity names and conversion rates for three forest types in central Georgia

Definition of quantity name	Quantity name and value
TYP1 converted to TYP2	CT12=.68
TYP1 converted to TYP3	CT13=.32
TYP2 converted to TYP1	CT21=.26
TYP2 converted to TYP3	CT23=.74
TYP3 converted to TYP1	CT31=.12
TYP3 converted to TYP2	CT32=.88

different rates. By using the Georgia data (Boyce and McClure 1975), these conversion rates are calculated and inserted into the model as values for CT12--CT32 (table 14). Note that the sum of the reversion rates from a type, CT13 plus CT12, should equal 1 unless the manager intends for some proportions of the reversions to be lost from the forest.

Insert the reversion and conversion rates into the model. Changes in potential timber indices, deer habitat, and cash flows can be examined for different silvicultural modes and different reversion and conversion rates. For a given silvicultural mode, what is the affect of reducing the pine reversion rate to 0.1?

Reductions in pine reversion rates incur costs for reducing the regeneration and the growth of hardwoods. In the economic algorithm, write equations for the outflows of money to reduce pine reversion rates. The costs for different kinds of culture depend on the area of pine harvested at time K, H1.K. These costs for the initial pine regeneration are added costs to obtain the total

costs for reducing the pine reversion rate. These costs are added to the total outflows (OT.K); any inflows that may result from regenerating the harvested land to pine, such as tax incentives, are added to the total inflows (IN.K) (fig. 68).

Use some realistic costs and tax incentives to examine potential returns from regenerating pines after the pine harvest. When and how do such investments change NPV and EAR? How do discount and reinvestment rates interact with investments in pine regeneration to change the values of EAR?

Analyses similar to the preceding one can be made to evaluate the benefits expected from converting oak-pine and hardwood stands to pine. These kinds of analyses can be compared with silvicultural modes that are dependent on scheduling harvest rates, opening sizes, natural regeneration, and natural conversion rates. Differences in EAR are appropriate for examining economic differences in relation to other benefits.

Some management policies require a certain proportional distribution of different forest types. The results of this kind of policy can be simulated with DYNAST by using the controls for reversion limits, RL (fig. 69). For example, the original inventory for the Georgia forest indicated 44 percent of the area was in the pine type. I assume that no regeneration investments will be made until the pine type declines to 20 percent of the forest. The intent is to fulfill a policy that says diversity of habitats for some plants and animals requires 20 percent of the forest to be in pines.

The "Analytic Silviculture Controls" are used as follows. The reversion limit for the pine type, RL1, is given the value equal to 20 percent of the total forest area, RL1=1278 acres. The pine type will revert after harvesting at the natural rates until the area of pine type, TYP1, equals 1,278 acres (table 14). When this limit is reached, a cost will be incurred to maintain the pine type.

The cash outflows for regenerating pine are 0 until the 20 percent limit for pine is reached, then outflows are begun in the cash flow algorithm. This simulation is achieved in the model with the limit function FIFGE. In the cash flow algorithm the costs for pine regeneration are multiplied by 0 when no regeneration costs are incurred and by 1 when there are outflows for regeneration. The switch is controlled in the function FIFGE with the arguments: 0,1,TYP1.K,RL1. The multiplier is 0 until the pine type equals RL1, then the multiplier is 1. The reversion limits for oak-pine, RL2, and for hardwoods, RL3, remain 0.

All of the reversion limits, RL1, RL2, and RL3, may be given values simultaneously if the sum of the values is less than or equal to the total area of the forest.

A Checklist for Silviculture Controls

DRT is in years and is limited in the DYNAST program to a minimum of 1 year for timber removals after sales.

IIN and IOT are initial inflows and outflows in dollars.

CT12 plus CT13 should equal 1, CT21 plus CT23 should equal 1, and CT31 plus CT32 should equal 1. More area cannot be converted than is reverted and all reverted land should be converted to some use.

RL1 plus RL2 plus RL3 may have values from 0 up to the total forest area.

ISO_, initial opening size is a guide for in-place decisions.

ISD_, is the desired variance in opening size divided by 2.4 (Pugh 1983:28).

HC_--HG_ are harvest rates expressed as rotation periods or desired ages of harvest and are

measured in years. This control is used in conjunction with:

FC_--FG_, which are the fractions of a type rotating through the habitats. The sum of FC_--FG_ must equal 1 because it is not possible to rotate more or less than is in the real forest.

When a harvest age, H_, is given in years, no area is diverted from the habitat to seedlings unless a fraction to be rotated, F_, is also given.

When a fraction, F_, is given and the harvest age, H_, is 0, the appropriate area is diverted to seedlings with the minimum age for the habitat being used as the harvest age.

CR_--GR_ are reversion rates with the range 0 to 1. Conversions by natural mortality occur only from the oldest age class. For example, when the age range for an old-growth habitat is from 121 to 300 years (table 13) and all harvest controls, HG_ and FG_, are 0, the natural mortality rate is based on 300 years. If a reversion rate, GR_, is given, the area reverted at time K will be the reversion rate multiplied by the natural mortality rate for a 300-year rotation period.

The maximum reversion rate can be 1 for all habitats simultaneously but no reversions occur, except as noted above, unless timber is harvested; that is, a value is given to F_ for the habitat.

IA_--IG_ are the initial inventory; CS_--GS_ are the areas of timber sold and standing; TTY_ is the yield table; YST_ is the yield standard; and TMR_ is the rotation period for the type. Any of these constants and the yield table may be changed in reruns.

TSLF, the sell fraction table, can be changed in reruns to examine alternative policies for harvesting accumulated timber such as for forests composed mostly of old-growth stands.

Chapter 9

Conservation of Biological Diversity

Overview

Diversity is being different. Biological diversity means differences in elements such as genes, amino acids, flowers, species, and plant and animal communities. Information about diversity is usually expressed as the distribution of items, such as individuals, among different classes of an element, such as a species. This chapter is concerned with biological diversity and its conservation.

The phrase "biological diversity" and the word "diversity" are used in silviculture, forest measurements, land management, planning, wildlife management, and forest insect and disease management. In a managerial context, diversity is maintained or increased to provide human benefits.

Many biologists use diversity in a functional rather than a managerial way. The functional approach is to search for an understanding of the functioning of forest communities rather than directing the forests to provide human benefits. The functional approach leads to the computation of many multifaceted diversity indices (Hutchinson 1978; May 1976; Pielou 1977; Southwood 1978; Whittaker 1972). These indices are useful to some biologists but are not especially useful to forest land managers, silviculturists, and wildlife managers.

Public concern for maintaining certain kinds of diversity in renewable resources is expressed in the National Forest Management Act of 1976 (USDA FS 1983a). The Act requires that diverse plant and animal communities be provided to meet multiple use objectives. The Act specifies that

steps be taken to preserve the diversity of existing tree species. To meet these provisions, alternative management plans and definitions must be developed.

The purpose of this chapter is to define "diversity" as it applies to forest management and to discuss concepts relative to maintaining a desired stability of forest plant and animal life. Data presented support the contention that the natural succession of forest stands be monitored for use in making management decisions, assuring diversity, and keeping multiple use objectives congruent with consumer attitudes toward social and economic benefits.

Defining Biological Diversity

The kinds of animals, plants, and microorganisms differ within and among forest stands. As time progresses, these renewable resources change in kind and in proportion from place to place. These variations are recognized as "diversity," which is the condition of being different. The classification, measurement, and control of the elements that make up forest and range diversity are activities associated with managing renewable resources. It is the proportional distribution of diverse situations, such as different combinations of species and habitats, that determines the availability of timber, wildlife, range production, recreation, streamflow, esthetics, and other benefits (Boyce 1977, 1978b; Flood and others 1977; Siderits and Radtke 1977).

Classification, mensuration, and statistical sampling techniques have been developed to distinguish and measure differences in the elements of communities (Husch and others 1972; Wenger 1984). These elements include tree species, forest types, animal and plant populations, timber volumes, browse and hard mast, stand age classes, site index, and stand condition classes. Thus,

these differences, which are viewed as renewable resource diversity, are defined. Criteria are specified so that one animal species can be consistently distinguished from another; continuums, such as tree diameters and stand conditions, can be separated into classes; and differences in management decisions can be statistically determined.

Briefly, a definition of renewable resource diversity is the differences in the elements of the biological communities. The criteria are:

1. Identify elements of the community that are being considered (i.e., tree species, bird species, forest types, stand conditions, age classes).

2. Specify measurements or characteristics that evaluate or distinguish elements (i.e., differences between species, measurements for classes of a continuum).

3. Describe how the differences between elements are meaningful for management decisions (i.e., stand condition classes, plant or animal habitat, tree sizes, and the wood product potential).

This definition of "diversity" is essentially the same as in most dictionaries. The criteria provide the scientific basis for different people to repeat observations and measurements and, thus, provide scientific credibility for management decisions (Bridgman 1927).

Relation of Diversity to Benefits

A well-known concept for providing a timber benefit helps to illustrate how resource diversity is related to a benefit. Timber can be harvested only from stands that have trees large enough to meet a definition for timber. I define "timber"

as trees 11 inches d.b.h. and larger and define a mature-timber stand as one with half of the dominant and codominant trees qualifying as timber. If a forest has no timber, no timber benefits can be derived immediately. If all the stands in the forest are mature, the maximum timber benefit can be achieved in the shortest time. However, if an annual timber benefit is desired for a long period of time, it is necessary to bring about a diversity of ages and areas for each forest type (Smith 1962). If the age class difference is chosen to be 1 year, the maximum stand area for each age class equals the forest area divided by the time required for stands to mature. Other diverse combinations are possible.

The diversity of stand area and age classes provides benefits other than timber. For example, certain benefits for deer are provided by browse in the seedling years, by some hard mast as the stands approach maturity, and by cover in the sapling years (USDA FS 1979). During the seedling years the proportions of some kinds of spiders increase (Coyle 1981). If the annual age class diversity is changed, the timber benefit, the deer habitat, the species of spiders, and other benefits will change. It is the state of forest organization (in this example the annual age class diversity) that determines the availability of multiple benefits.

This example illustrates one way diversity of specified elements of renewable resources can be used to make management decisions about the availability of specified benefits. It also illustrates the theory for multiple benefits: "the kinds and proportions of states of organization determine the kinds of proportions of human benefits available from a forest" (Boyce 1977).

We can now consider how reducing the proportion of habitats reduces the availability of benefits. Consider first a random distribution

of 80 age classes, each differing by 1 year. Such a distribution can be maintained by regulating the harvest rate and the opening size. Without a scheduled harvest and opening size, the larger trees increase in size and constrain both the opening size and the proportion of stands in the younger age classes. In time the younger stands represent less of the forests. Correspondingly, benefits related to stands in the younger age classes decline, which affects the habitat diversity.

If we take the appropriate action to increase the size and proportion of stands in the younger age classes, both the habitat diversity and the availability of certain benefits increase. Not only can timber be harvested periodically, but also habitat can be provided for an increased number of species. From Coyle's (1981) research, we can expect to provide habitat for the largest number of species when the 1-year age classes are present. This leads to another useful concept about diversity: An increase in the diversity of habitats increases the habitat for diverse kinds of organisms.

Much of the evidence for this concept comes from studies of plant and animal evolution, migration, and extinction. As illustrated by numerous examples (Dobzhansky and others 1977; Harper 1977; Mayr 1970; Stebbins 1974), regions having many different habitats are more likely to have greater diversity of genotypes than regions with a few habitats. This fact is supported also by evidence that organisms with chromosomal variations are more likely to survive in the transition areas between habitats than in a large, uniform habitat. This concept is used as a basic principle when evaluating habitats for wildlife (Flood and others 1977; Siderits and Radtke 1977). When dealing with a certain species and with known habitat requirements, the operational criteria for diversity can be specified.

Southwood's (1978:429) guide to the analysis of diversity emphasizes the importance of examining the form and the meaningfulness of the data. He considers these steps an operational approach especially important now that computerized data collection and analysis tempt investigators to compute diversity indices without knowing the criteria. Indices without criteria can become "black boxes" that are difficult to use in different situations, that are difficult for different people to reconstruct, and that may lack scientific credibility.

Two features of diversity should be made explicit. The first feature is the items of diversity. The items of primary interest are tree species and plant and animal communities. Taxonomic texts define species, and ecologic concepts can define communities. Specifications for classes of these items are taken or modified from taxonomic treatments and from published descriptions of forest types and habitats. Any set of classes for any item, such as tree species, communities, soils, site index, and yield values, should have explicit operational criteria.

The second feature of diversity is distribution. It is important to know how the items are distributed among the classes. For example, species are often ranked by the abundance of individuals; diameter classes are ranked from the smallest to the largest; habitat classes are ranked by kinds of dominant species, stand ages, and stand areas.

One of the most informative ways to communicate information about diversity is to use a table. Table 15 displays the distribution of items (forest types) for certain elements (forest areas). Diversity or difference is apparent from observations of the table. If desired, quantitative values for difference can be computed from the data. Tables of this kind are simple ways to convey information about diversity.

Table 15.--Diversity of forest types found on the Pisgah and Nantahala National Forests and the Mountain Region Survey in North Carolina (in percent)

Forest types	Pisgah National Forest	Nantahala National Forest	Mountain Region Survey
White pine-hemlock	2.4	--	3.4
Spruce-fir	1.2	--	0.3
Loblolly pine	--	1.7	0.4
Shortleaf pine	--	--	0.6
Virginia pine	1.5	--	5.3
Pitch pine	7.1	1.2	1.4
Oak-pine	4.8	7.7	8.7
Oak-hickory	74.5	63.4	69.5
Chestnut oak	7.7	18.4	4.5
Elm-ash-cottonwood	--	--	0.2
Maple-beech-birch	2.8	7.5	5.7

From Boyce and Cost (1978). See Cost (1975) for definitions.

A simple graphic method is often effective for communicating diversity. A common technique is to array the items, such as forest types, in order of abundance, and plot the distributions (fig. 70). The curves display the differences (diversity) even though the forest types (classes) may be ordered differently from the areas and elements. The graphic method has many variations (May 1976; Pielou 1977; Southwood 1978).

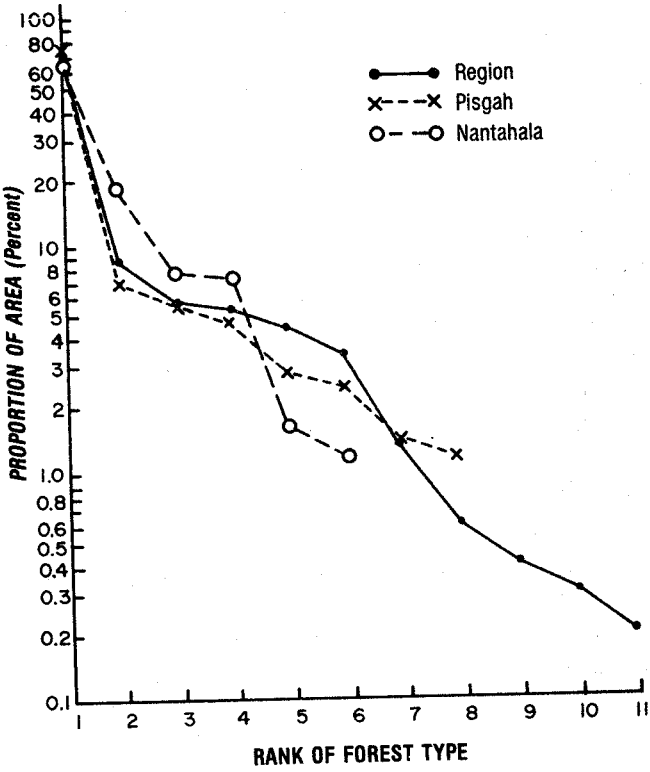

Figure 70.--Example of a chart for displaying diversity. Items, the percent of forest types, are plotted by rank for three forest areas. (Data are from table 15.)

Tables communicate the most information about diversity; graphs and charts convey less information; and diversity indices, especially the confounded form (Pielou 1977), display little meaningful information for silviculture and management planning.

The intent of each table, chart, and graph should be to convey information about the distribution of items among defined classes of an element. The displays should communicate the differences within and among the elements. It is important to integrate information about diversity of forest communities and tree species with multiple benefits. And there should be a way to integrate the information about diversity into land management plans.

Diversity in Land Management Planning

Diversity results from the state of forest organization, which is defined as the proportional stand distribution by age classes, area classes, and forest types. Changes in the distribution of these stand classes affect timber, wildlife habitat, scenic value, streamflow, and other benefits. Diversity of communities and tree species is determined by the distribution of these stand classes. For each planning area, criteria are specified for stands by age, area, and type classes (Boyce 1977). Type classes are defined by tree species diversity.

The distribution of stand classes (figs. 4, 5, 6) is the common denominator for multiple benefits, diversity relations, and management plans (Boyce 1977). Projected distributions are the bases for estimating potential timber yields, present net values, potential streamflow, scenic values, and plant and animal habitat in relation to organizational states.

On the Nantahala National Forest in North Carolina, Coyle (1981) identified 134 kinds of spiders in four stands. One stand was a mature-timber habitat; the other three were seedling habitats from 1 to 5 years old. Some species of spiders lived in both kinds of habitats, some only in the mature-timber stand, and some only in one or more of the seedling stands (table 16). From Coyle's description, I translated the biological information into a forest management structure (Boyce 1981).

Table 16.--The number of species of spiders found in a mature stand and in three seedling stands in the Southern Appalachians

Ecological category	Stand type			Total
	Mature	Mature and one or more seedling	One or more seedling	
Sedentary litter spiders	4	16	18	38
Hunting spiders	4	16	39	59
Aerial web builders	12	10	15	37
Total	20	42	72	134

Source: Coyle (1981).

The translation (table 17) mathematically relates the biological information to the proportional distribution of age classes in the stands. The spider habitat is scaled from 0 to 1. A loss of either all seedlings or all mature timber would threaten the habitat for some species of spiders. This information integrates the spider habitat with other multiple benefits and makes it possible to project alternative land management plans based on these integrated benefits. This technique can be used for any forest type or plant and animal group, guild, or community.

Table 17.--Habitat index for spiders limited to seedling or mature-timber stands as related to organizational states of the forest in the Southern Appalachian Mountains

Habitat index (dimensionless)	Seedling habitat	Mature timber
	- - - - Percent - - - -	
0.0	0.0	--
0.1	1.0	0
0.2	1.3	10
0.3	1.7	12
0.4	2.0	16
0.5	2.5	20
0.6	3.0	25
0.7	3.5	30
0.8	4.0	40
0.9	4.8	50
1.0	7.0	70

Source: Coyle (1981).

One plot, modified from the DYNAST simulation program, illustrates how to project the potential timber production in relation to the potential habitat for spiders for one alternative plan (fig. 71). It also estimates net present values. These potentials and all other forest benefits change with changes in stand age classes. This kind of information about diversity is important for decisions to control the organizational state of a forest.

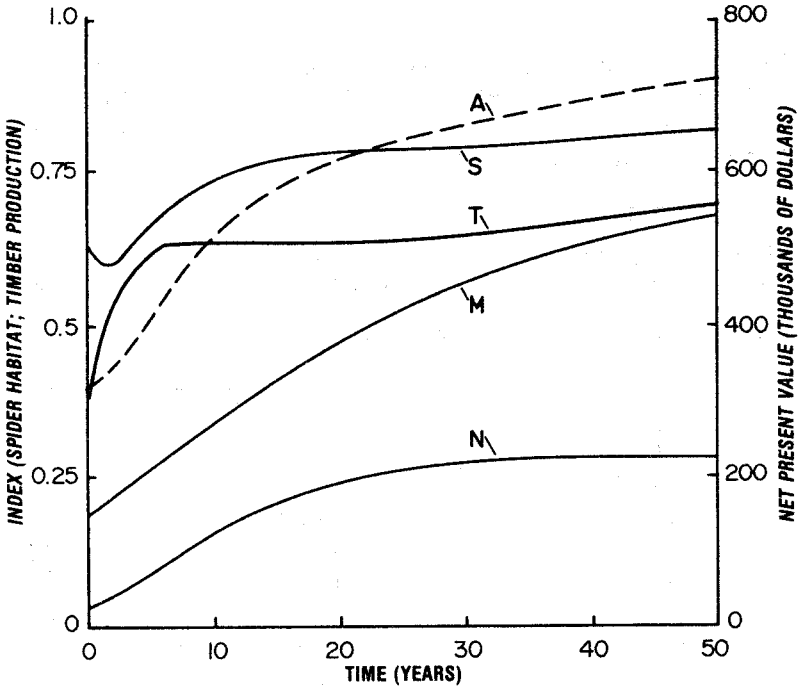

Figure 71.--Example showing diversity of animals integrated with other benefits by a DYNAST simulation for one silvicultural mode.
A = spiders found in both mature and seedling stands
S = spiders found only in seedling stands
T = potential timber production
M = spiders found only in mature stands
N = estimate of net present value

Diversity in the National Forest Management Act (NFMA)

A section on diversity in the NFMA reflects a deep-seated ethic among many constituencies to live in harmony with nature. This ethic involves providing habitat for diverse plant and animal forms and maintaining diverse natural plant and animal communities. Fulfilling this concern requires that a forest consist of different forest types. Forest types, such as hardwood types and pine types, are defined by tree species diversity. The signals from constituents to the Congress focused on perceptions of a decline in the forest type diversity and a decline in the potential habitat for some plants and animals that might result from converting eastern hardwood types to pine types. A summary of this information is given in the legislative history of the Act (U.S. Senate Committee on Agriculture 1979). Some of the items to be noted from the Act's history are:

1. In the dictionary meaning for the word "diversity," difference seems to be used.

2. A primary concern of constituencies is to maintain different kinds of natural plant and animal communities and different tree species associated with different forest types.

3. The forests are to be manipulated and directed to provide biologically possible combinations of benefits, including providing habitat for a diversity of plants and animals.

4. Diversity is to be related to multiple use objectives.

Diversity of tree species and plant and animal communities is a consequence of the forest's transformation from state to state. The transformation may be either natural or directed by silviculture. What is needed to implement the diversity section of NFMA is a way to relate information about multiple benefits to projections of organizational states of a forest. The projections should describe multiple benefits and diversity of forest types and communities expected from alternative silvicultural modes. The projections are parts of alternative plans and are a source of information for making decisions and for controlling the forest.

The Important Points

An operational definition for biological diversity makes it possible for different people to repeat observations and measurements and thus give scientific credibility to management decisions.

Information about diversity can be conveyed by tables, charts, and graphs that display the distribution of items among defined classes.

Simulation methods such as DYNAST can integrate information about diversity and multiple benefits. These integrations are useful for developing, analyzing, and choosing among alternative land management plans.

DYNAST simulations are valuable primarily as media for communicating explicit information--the biologically possible combinations of benefits, including diversity of forest communities and forest types, integrated and projected for alternative silvicultural modes.

When a combination of benefits--one of the DYNAST projections--is chosen, it identifies a single silvicultural goal. This goal directs the forest transformations toward the desired organizational state that provides the desired biologically possible combination of benefits, including diversity. Actions of all disciplinary areas of management can be integrated and directed toward this single goal.

Decisions are made by people responding with insights and experience to the use of management resources and to changes in social, economic, and political forces. The options for choice, the DYNAST simulations, are kept congruent with the real forest by information from inventories, monitorings, and research.

Chapter 10

The Use Of Biological Diversity

Overview

Diversity, the distribution of items among classes of elements, provides information about the availability of component parts for different kinds of systems. For example, the diversity of a randomly stacked pile of automobile parts is the same as the diversity of parts in an automobile. Both the pile of parts and the automobile are systems; each behaves differently because each has a different structure. Information about biological diversity is useful because it removes uncertainty about the availability of parts (such as organisms) for structuring a system (such as an ecosystem).

Because of this kind of uncertainty, a section on diversity was included in the National Forest Management Act of 1976 (ch. 9). The desire for biological diversity comes from the deep-seated feeling of uncertainty about the future. This uncertainty about man-caused extinctions of organisms is so universal that a widespread ethic of good conduct requires public and private investment to preserve endangered and threatened species.

This chapter is about the use of biological diversity; the widespread ethic of living in harmony with nature; and forest eudemonism, a system of ethics for evaluating forestry actions in terms of their capacity to provide a livelihood, happiness, and well-being for man.

Forest Eudemonism

Forests are an essential element for the happiness and well-being of man. The earth without forests would be a difficult place for man to live.

The simple observation that is significant for forestry is: The elements of eudemonia are valued for their diversity and structure. Eudemonia for most people involves the amounts and availability of food, clothing, shelter, water, and some other elements of one's environment. This is diversity as defined in chapter 9, and availability is determined by the system's structure. What is significant is how this diversity and structure contributes to the potential livelihood of man and to man's living in harmony with nature. A desired diversity of eudemonistic items cannot be chosen from alternative sets by comparing only differences in net present values, equivalent annual costs, or diversity indices. The monetary values of the alternatives as measured by net present value are economically important, but economics, when considered outside of the context of diversity of organisms--such as spiders--can lead to poor decisions. Another example is water, which is important for life. But when one has enough water, it is a poor decision to procure more water regardless of the marginal price.

The displays of cash flows are related to the potential habitat for noncommodity species, to visual appeal, to wilderness appreciation, to streamflow, and to commodity items. The cash flows cannot be allocated to the different items. For example, limiting cash flows to the sales of commodities does not constrain the treatment effects to commodity items. The cash outflows for cultural practices change the forest's organizational state and thus change the diversity of most items. Cash flows are viewed as effects of a mode of silviculture (figs. 4, 5, 6).

Some people have different perceptions of eudemonia. Some interested parties may view forests only as sources of cash flow, and others may have an interest only in opportunities for hunting and what those opportunities cost. The use of different algorithm combinations and their associated white boxes provides opportunities for valuating forests in eudemonistic terms.

Diversity, Eudemonism, and Management

Biotic variety and the abundance and distribution of the elements are ultimately controlled by variety in the physical environment. Variations occur in such factors as moisture regime, climate, physiography, geology, land form, and soil. Beyond these, diversity is a consequence of continued changes in species, stand ages, stand areas, and patterns from one state of ecosystem organization to another (ch. 8). These dynamic transformations are both natural and man-influenced through such activities as timber harvest, livestock grazing, water development, wildlife population management, prescribed fires, and so on. The multiple-resource products of a forest are also the results of these transformations. They are ultimately controlled by the productive capacity of land as determined by physical factors that control ecosystem productivity. Thus, diversity and the multiple-resource production both derive from the same set of physical conditions, natural processes, and man's cultural activities (ch. 3). The common denominator for diversity, eudemonism, and management is the organizational state of a forest and the transformations from state to state.

Applying the concept of biological diversity requires determining how a silvicultural mode changes diversity in the elements of the ecosystem; determining how these changes in diversity change linkages among the elements and thus the ecosystem

structure; and evaluating the significance of these changes in terms of the potential livelihood, happiness, and well-being of man. Many examples are found in the literature. The examples given here evaluate the consequences of using clearcutting to harvest timber in the Southern Appalachian Mountains near Highlands, NC (Bruce and Boyce 1984).

The Highlands Example

In 1974, the Highlands Biological Station, the Southern Region of the USDA Forest Service, and the Southeastern Forest Experiment Station began a series of cooperative research agreements designed to examine the effects of timber harvest on biotic diversity in Southern Appalachian hardwood forests. The project was undertaken in the context of the DYNAST model.

The initial studies were designed to utilize recently clearcut stands near the Highlands Biological Station. All of the sites were within the Highlands Ranger District of the Nantahala National Forest. The area lies near the southern terminus of the Blue Ridge Physiographic Province. In 1975 four sites were chosen that were similar in area, elevation, slope, exposure, and precut overstory vegetation. Two additional sites were added in 1976 and 1978. Based on timber cruise data and inspection of adjacent forests, the overstory before cutting was dominated by oaks (*Quercus alba* L., *Q. prinus* L., *Q. rubra* L.), hickories (*Carya* spp.), and, at some sites, white pine (*Pinus strobus* L.). Elevations ranged from 2,800 to 3,900 feet. A summary of the characteristics of the six sites is given in table 18.

Replicated sampling areas were established in the clearcut stands and in adjacent uncut forests. Comparisons were made between clearcuts and adjoining forests and between clearcut stands

Table 18.--Characterization of the study sites

Site	Year cut	Size	Slope	Aspect	Elevation
		Acre	Degrees		Feet
Horse Cove	1972	39	2-10	130	3,100
Brush Creek	1973	39	5-10	150	3,900
Rich Mtn. North	1974	35	10-15	130	3,900
Ellicott Rock	1975	20	5-12	100	2,800
Buck Creek	1976	25	20-30	20	3,190
Rich Mtn. South	1978-79	27	15-25	234	3,190

of different ages. Intersite comparisons such as the latter are confounded by heterogeneity among sites. However, comparisons within sites in successive years will be possible eventually. The study focused on vegetation and nongame animals, with particular attention to animal groups having important ecological roles in the forest community. Sampling methods differed according to taxon.

One concern was to discover how forest managers influenced diversity when no experimental or research constraints were placed on managerial decisions and controls. Care was taken not to influence and not to be involved in the decisions and actions of the forest management organizations.

To date, the studies have included plants, birds, small mammals, terrestrial salamanders, and predatory arthropods. Only the latter are used to illustrate this example.

Predatory Arthropods

Four groups of predatory arthropods have been investigated: spiders, harvestmen, centipedes, and ground beetles. Because these are generally large taxa with many species, the results have provided a rich body of data on diversity changes accompanying

timber harvest. For three of the four groups the results exhibit a common trend; this suggests that a common mechanism is operating to regulate diversity among these animals.

The first of the arthropod studies was conducted in 1976 on spiders (Coyle 1981). Three clearcuts (Ellicott Rock, Buck Creek, Horse Cove) and one uncut forest (Ellicott Rock) were sampled. Because of the ecological diversity of spiders, four sampling methods were used: pitfall trapping, leaf litter sampling with Tullgren funnels, aerial sweep-net collecting, and hand-collecting. For each method, an attempt was made to equalize the sampling effort among sites. Although total sampling efforts were approximately the same at the four sites, within a site there was no way to equalize sampling efforts among methods because the efficiencies of the methods vary. Thus, the individual samples do not necessarily reflect actual species abundances. Moreover, some habitats were not sampled (e.g., arboreal habitats in forest canopy). The collecting schedule favored species active during the day in the summer.

Coyle's collections yielded 1,729 individuals and 134 species. He sampled three clearcuts, but sampled the adjacent forest at only one site (Ellicott Rock). Thus, the evaluation of the Ellicott Rock forest and clearcut samples represents the most reliable comparison from these data.

Coyle classified spider species according to stratum (ground versus aerial) and prey capture mode (web builders versus cursorial hunters). Four guilds were recognized--ground web builders, ground hunters, aerial web builders, and aerial hunters. Species composition differed markedly between the spider faunas of the Ellicott Rock forest and the clearcut sites--both species and individuals were reduced on the clearcut. Despite the lower species richness at the Ellicott Rock clearcut, the value of the Shannon index (Pielou

1977) was greater in the clearcut sample. Further analysis showed that the decrease in species at Ellicott Rock was largely due to a loss of both ground and aerial web builders. Hunting spiders, particularly ground hunters, had increased. The decrease in dominance of web builders together with the influx of hunting spiders accounted for the increase in the evenness component of diversity. Coyle argued that the change in vegetation structure and microclimate brought about by clearcutting favors the more mobile hunting spiders, many of which seem well adapted to open and climatically variable environments. Data from the other two clearcuts, which were not paired with adjoining uncut forests, seemed to support his arguments.

Two other groups of predatory arthropods, harvestmen (or daddylonglegs) and centipedes, were studied in 1978 and 1979 by Summers.[1,2] Transects were established in an uncut forest adjacent to Ellicott Rock and in clearcuts at Ellicott Rock, Brush Creek, Horse Cove, and Rich Mountain North. In 1979 an additional study of harvestmen was made in a cove forest and forest ecotone. Line transects were established, and sampling points were randomly selected for pitfall trapping and litter sample collecting. Arthropods were extracted from the litter by using Berlese funnels and were hand-collected for set time periods at each site. Thus, an attempt was made to equalize the sampling effort among sites. For centipedes, Summers used transplanted logs, which had been fumigated beforehand, to supplement collection of log-dwelling species. Sets of logs having equivalent under-bark areas were placed at

[1]Summers, Gerald. The effects of clearcutting on opilionid populations in the Southern Appalachians. Unpublished report on file. Highlands, NC: Highlands Biological Station; 1979.

[2]Summers, Gerald. The effects of clearcutting on chilopod populations in the Southern Appalachians. Unpublished report on file. Highlands, NC: Highlands Biological Station; 1980.

each site for an 8-week period in July 1978 and were then dissected for centipedes. In addition Summers measured structured features of the canopy, understory vegetation, litter, and soil.

Both species richness and abundance of harvestmen in the region were low in comparison with the other arthropod groups. Summers found fewer species on clearcuts (one to three) than in the uncut forest (five); he attributed the differences to the greater microclimatic extremes resulting from clearcutting.

The centipede faunas of the study sites were richer in both species and individuals. Summers recognized log and leaf litter species assemblages and noted a differential response to clearcutting between them. Species richness and abundance were higher in all litter samples from clearcuts than in litter samples from the uncut forest; an opposite trend was found for log samples. Overall, species richness and diversity as measured by the Shannon index were greater in the clearcuts than in the uncut forest. Summers related these findings to several habitat variables, particularly habitat space in litter.

A major study of ground beetles was conducted every spring and summer from 1979 to 1981 (Lenski 1982). To determine the composition of the beetle fauna, Lenski sampled three clearcuts--Rich Mountain South, Rich Mountain North, and Ellicott Rock--each of which was paired with an adjacent uncut forest stand. At each site four sample areas were established, two in the clearcut and two in the forest. Each area consisted of a 20- by 20-foot grid of pitfall traps. All sample areas were located from 98 to 164 feet from the forest-clearcut edge. Traps were visited daily, and most ground beetles were identified to species in the field and then released. Sampling was conducted for about 50 days at each site in 1979 and for an additional 64 days at Rich Mountain South in 1980.

Lenski's detailed and exacting experiments support the concept that species interactions, particularly competition, may represent factors that explain some changes in species abundance following timber harvest. Yet his experimental work encompassed only two species and, as Lenski admitted, other beetle genera that show the same pattern may be regulated by other mechanisms.

The one trend exhibited by the several arthropod studies is an increase in intrageneric species diversity following harvest due to reduced abundance of dominant species. This trend is highly significant in ground beetles where the samples from all three clearcuts have higher diversity than the corresponding uncut forest controls. For spiders and centipedes, only one clearcut (Ellicott Rock) was paired with an immediately adjoining forest, but in each case intrageneric diversity was greater in the clearcut than in the forest. The other two clearcuts studied also showed higher values of intrageneric diversity for spiders than did the Ellicott Rock forest. But for centipedes the results were more variable when three other clearcuts were sampled.

The trend toward increased intrageneric diversity with timber harvest was not apparent for harvestmen, probably because there were few species and few individuals of each species. Although Lenski was able to relate this trend to competition in one beetle genus, it is by no means determined that this explanation applies to the other taxa. Additional experimental studies would be helpful to resolve this problem.

Discussion of Findings

Generalizations from these studies are tentative because the oldest clearcuts are only 10 years old and the rotation ages for these forests are more than 80 years. However, some relations are apparent.

The studies conducted at Highlands show that timber harvests diversify the fauna within some taxonomic groups, although work to date has dealt only with early successional communities. Coyle (1981) found that the species composition of the spider fauna at the Ellicott Rock clearcut differed markedly from that in the adjacent forest; about 50 percent of the species found in samples from one habitat were not found in those from the other. Guild representation shifts, which indicates that the differences were partly due to cutting. Similarly, in 1976 Horn[3] noted differences in the breeding bird communities among young clearcuts; such differences reflected habitat diversity. Later, Van Voorhees[4,5] found that timber harvest diversified the small mammal community. Thus, in these and probably many other animal groups, creating openings diversifies habitats and provides a mosaic of stand conditions in which more species can exist than in uniform stands of mature or old-growth timber.

Timber harvesting can be viewed as a means of generating and directing biotic diversity. First, the creation of openings that differ in size and the subsequent vegetational succession produces a mosaic of different habitats and provides livelihoods for a greater variety of species than is found in uniform stands of mature forest. Additional variety in kinds of habitats results from forest type conversion. Second, harvesting can be viewed as a disturbance that accentuates

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[3]Horn, John. Avian succession following clearcutting in the Southern Appalachians. Unpublished report on file. Highlands, NC: Highlands Biological Station; 1976.

[4]Van Voorhees, David A. Small mammal succession following clearcutting of southern Blue Ridge forests. Unpublished report on file. Highlands, NC: Highlands Biological Station; 1978.

[5]Van Voorhees, David A. Early responses of small mammals to forest clearcutting. Unpublished report on file. Highlands, NC: Highlands Biological Station; 1981.

nonequilibrium, relaxes competition, and thereby allows greater diversity. What is needed to further test these ideas are (1) additional paired comparisons of flora and fauna in uncut and cut forest stands that include all major successional stages but pay special attention to intermediate stages, and (2) experimental manipulations within selected taxa designed to elucidate the role of biotic interactions in regulating diversity.

Translation of the Highlands Data

The basic data generated from sampling programs of this type are lists of species and abundances. From a management viewpoint the best index of diversity available from such data is probably the number of species found or species richness. It is impractical, if not impossible, to sample the total flora and fauna. Therefore, sampling from species lists of selected components, representing important taxonomic and functional groups, probably represents a reasonable approach to evaluating the effects of a given management mode on total species diversity.

In chapter 9, I illustrated the method of translating the data derived for spiders into a managerial format. This is an easy procedure because the spiders are found in discrete groups according to habitat type (table 16). Most of the ground beetles are found in both the seedling and mature-timber habitats (table 19). These two kinds of habitats have important differences, which are translated into white boxes for use in the DYNAST model.

Eleven species of beetles, comprising 38 percent of the individuals trapped, seemed to be favored more by the presence of mature timber than by seedling habitats (table 20). Seven species, comprising 14 percent of the individuals trapped, seemed to be favored more by the presence of

seedling than by mature-timber habitats (table 21). For 27 species, about 48 percent of the individuals, differences in abundance were not consistent between the habitats. This latter group has little significance for management because these species of beetles can apparently survive in both habitat types (table 19). Our concern is to provide for species whose livelihood is enhanced by a particular habitat.

One supposition is: A silvicultural mode that maintains the most seedling habitats will enhance, up to a limit, the habitat for seven

Table 19.--Distribution of ground beetles trapped in mature-timber and seedling habitats, by habitat group

Habitat group	Habitat type		
	Mature timber	Seedling	Total
	Percent		Number
All individuals trapped	54	46	4,727
No difference in abundance	53	47	2,214
Most abundant in mature timber	69	31	1,837
Most abundant in seedling habitat	13	87	676

Source: Lenski (1982).

species of ground beetles (table 21). The upper limit on the amount of seedling habitat is about 6 to 7 percent in these hardwood forests because rotation periods are longer than 70 years. Shorter rotations could increase the amount of seedling habitat, but the amount of habitat for other organisms would be decreased. Thus, the habitat for these seven beetles is at the maximum

Table 20.--Ground beetle species found in consistently greater numbers in mature-timber (M) than in seedling (S) habitats on three sites

Species	Rich Mountain South		Ellicott Rock		Rich Mountain North	
	M	S	M	S	M	S
	- - - - - - - - - - Number - - - - - - - - - -					
Carabus limbatus	603	371	21	5	21	6
Macronetus debilis	28	3	68	16	34	6
Scaphinotus andrewsi	7	2	5	1	0	0
Scaphinotus guyoti	13	5	3	0	5	1
Scaphinotus irregularis	10	10	2	0	6	0
Scaphinotus violaceous	14	3	9	3	5	0
Spaeroderus canadensis	18	0	19	1	22	7
Spaeroderus stenostomus	15	0	18	2	0	0
Harpalus carolinae	143	72	40	10	125	42
Pinacodera limbata	6	0	0	0	8	0
Pinacodera platicollis	0	0	3	0	0	0
Total	857	466	188	38	226	62

Source: Lenski (1982).

when 7 percent of the forest is in seedling habitats (table 22). When no seedling habitats are created by timber harvesting, the beetles are assumed to survive in minimum numbers. Thus, the white box value is set at 0.05 for the livelihood index. Between these limits, the waveform of the relation is assumed to be a sigmoid curve. This last assumption is not based on experimental data. The sigmoid curve reflects the unproven ideas that: (1) the smaller the number of seedling habitats, the farther apart the habitats will be for travel by the beetles and the less the probability the habitats will be in a suitable location for other habitat factors; and (2) the larger the

Table 21.--Ground beetle species found in consistently greater numbers in seedling (S) than in mature-timber (M) habitats on three sites

Species	Rich Mountain South		Ellicott Rock		Rich Mountain North	
	M	S	M	S	M	S
	- - - - - - - - - - Number - - - - - - - - - -					
Harpalus pennsylvanicus	3	120	6	103	0	26
Dicaelus dilatatus	0	10	1	25	0	3
Dicaelus politus	13	59	3	66	26	47
Anisodactylus interstitialis	0	1	0	4	0	0
Anisodactylus ovularis	0	5	0	0	0	1
Pterostichus adoxus	7	10	11	28	21	33
Galeritula spp.	0	1	0	14	0	29
Total	23	206	21	240	47	139

Source: Lenski (1982).

Table 22.--Data for white boxes translated from inventories of ground beetles to show part of forest that favors their potential livelihood, by habitat type

Percent of forest in seedling habitat	Livelihood for species listed in table 21 (dimensionless)	Percent of forest in mature and old-growth habitats	Livelihood for species listed in table 20 (dimensionless)
0.0	0.05	0.0	0.05
.01	.1	.1	.15
.02	.45	.2	.65
.03	.75	.3	.85
.04	.88	.4	.95
.05	.95	.5	1.0
.06	.98		
.07	1.0		

number of habitats, the closer the habitats will be for beetle travel between them and the greater the probability of the habitats being in a location that satisfies other factors of the beetles' habitat. Lenski's data indicate differences in habitat related to factors other than the presence of seedling or mature-timber habitats. See, for example, the data for Carabus and Scaphinotus, (table 20).

Another supposition is: A silvicultural mode that maintains the most mature-timber and old-growth habitats will enhance, up to a limit, the habitat for 11 species of ground beetles (table 20). No data are available for old-growth habitats. However, these older stands are not known to restrict the livelihood of these beetles. The upper limit on the amount of older stand habitat is about 50 percent in these hardwood stands. We do not have information on beetles for the age classes between seedling and mature-timber habitats. We assumed that as the seedling habitats age, some of the beetle species will decrease in abundance while others will increase to approach the distributions shown in table 20 when the stands are mature-timber habitats. Also, these data suggest that when there are no mature-timber habitats and older stands, the beetles favored by these age classes survive in small numbers. Thus, the limits for the white box are set at 0.05 when there are no mature-timber and old-growth stands and at 1 when half of the forest is in these older age classes. For the same reasons given above, the waveform of the relation is assumed to be sigmoid (table 22).

The data for white boxes may be plotted and adjusted as new information is received from research, experience, and monitoring. Most changes are likely to be adjustments in the waveform of the relations and few changes are expected in the limits. It is unlikely that new data will change the general direction of the curves.

Use of Diversity to Evaluate Effects

The white boxes for the two habitat groups of beetles are put into an algorithm. The potential habitats for alternate silvicultural modes are displayed along with the potentials for spider habitats (fig. 71), timber production, cash flows, and other effects (figs. 4, 5, 6). The valuation of the alternative silvicultural modes is determined by subjectively choosing the diversity of those effects perceived to provide optimal eudemony.

The evaluation of a forest ecosystem for human benefits must be based on diversity. This is true because no single number, index of values, cultural practice, or monetary amount can serve as a common denominator for the diversity of elements such as timber, cash flow, potential livelihood or kinds of organisms, visual appeal, and hunting opportunities. A cultural practice produces multiple effects including cash flows and raw materials for paper. The costs of a cultural practice cannot be rationally allocated among the eudemonistic effects. The value of the effect of a cultural practice is not the monetary value of the marketable elements but is the total contribution of the effects to the potential livelihood, happiness, and well-being of man. Information is in the displays of numbers and amounts of effects all linked to the common denominator, which is the transformations of the states of forest organization (fig. 4).

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Viewing the forest as a system that self-organizes in response to a schedule of harvest and culture provides a new basis for making forestry decisions. Computer simulations of states of forest organization through time provide displays of tne production of forest benefits ranging from timber and water to wildlife and recreation. From these displays, the manager chooses a desired schedule. Graphs are used to evaluate suppositions about future events. The responsibilities of managers are not usurped by computers; people make the decisions.

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