AN INTEGRATED RESOURCE MANAGEMENT PLAN COMBINING STELLA AND GOAL PROGRAMMING MODELS

by

Xianhua Kong©

A thesis submitted for the degree of

Master of Science in Forestry

Lakehead University

Thunder Bay, Ontario

March, 1993

ISBN 0-315-86193-2

ABSTRACT

Xianhua, Kong. 1993. An integrated resource management plan combining STELLA and GOAL programming models. 120pp.
Major advisor: Professor C. A. Benson.

Key Words: Integrated resource management, mutiple-use, STELLA, GOAL programming (GP), forest management alternatives, timber areas, sensitive areas

The primary objective of this study was to develop mathematical models with existing computer programs and to use these models to assist in providing useful information for multiple use planning. Two different models were used: 1) a system dynamic model (STELLA) and 2) Goal programming (GP). These two types of the models were combined to complement each other. Timber, wildlife (represented by moose), and forest aesthetics were selected as the three variables in this study. The modelling approaches of the two models were discussed. The STELLA model was developed based on past experience and knowledge, while the GP model was formulated based on the simulation results of the STELLA model. Gross merchantable timber and the dry weight of browse were used as goals in the GP model. Area constraints in the sensitive area (SA) zone were used to indicate aesthetic potential. The use of the two models was illustrated with a case study area, which is located in management unit 030 of Abitibi-Spruce River Forest, Northwestern Ontario. A thirty-year planning horizon and three management alternatives were employed. The results show that the STELLA model can help the forest manager to better his understandings of forest dynamic behaviour, and the solution of the GP model was improved by the reasonable goal levels set by using the simulation results from the STELLA model. As a result, the combination of two models made the integrated resource management planning more suitable and practical.

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ACKNOWLEDGEMENTS

I thank my major supervisor, Professor C.A. Benson, for his instruction, assistance, and encouragement while this study was being conducted. I also want to thank other members of my graduate committee, Dr. G. Hazenberg and Dr. H.G. Cumming for helpful comments and suggestions on this study.

Additional thanks go to Dr. H. Akervall, School of Outdoor Recreation at Lakehead University, for his knowledge about forest aesthetics in the study area, and to Mr. R. Strey from the Ontario Ministry of Natural Resources' Thunder Bay District Office for Providing materials (aerial photos, maps etc.) for field survey in the study area.

Finally, I acknowledge the Northern Studies (1991-92) Continuing Graduate Award, and support from the COFRDA research grant of Professor C.A. Benson.

INTRODUCTION

THE IMPORTANCE OF INTEGRATED RESOURCE MANAGEMENT

Forests have played and will continue to play a vital role in the life of man. From the time of early exploration, man's culture, way of life, and economic and social well-being have been linked to the forests.

For as long as people have thought about the future, they have managed forests (Davis and Johnson 1987). Past experience has revealed that forests play an indispensable role in maintaining our environment. Some natural disasters, such as flooding, drought, farmland desertification, and extinction of some species, have resulted from depletion of forests, as can be seen in some countries which used to have abundant forest resources. With the deterioration of our environment, the general public has shown increasing concern about preserving forest resources. The denudation of forestland is regarded as an offence against society, and irresponsible towards the next generation. Therefore, the task of the forestry profession is to protect, plant, and nurture our forests to ensure a continuity of growth for future generations.

The forest is a living system with many species of flora and fauna interacting. These flora and fauna form the forest ecosystems that provide the forest products desired by society (Young 1982). They produce not only timber, but also many other products and services, termed non-timber values, such as food and shelter for wildlife, erosion and flood control, the opportunity for recreational and aesthetic experiences.

With the development of our society, more products and services are expected from the forest. The values of non-timber resources appreciate and gain as much as timber (Bowes and Krutilla 1989). On the one hand, more groups in society become involved in the demand for forest products and services while on the other, forest resources become relatively scarce, as compared to past overabundance. As a result, conflicts among groups may occur. For example, in the United States, the conflict between those who would manage the stands for commercial timber and those who would preserve forest environments for recreational use was so intense that the issues that divided them were increasingly taken to court for adjudication (Bowes and Krutilla 1989). Under these circumstances, integrated forest resource management arose as a means of coordinating the various uses of forest resources. Therefore, a forest manager's role is no longer restricted to timber production, but is also expanded to the management of the natural resources that occur on, and in association with, the forest. At present, the forester can be defined as a land manager for all goods, benefits, and services that flow from the forest (Shirley 1983). Consequently, it becomes increasingly necessary for the professional forester to understand and manage the forest in a broader context than he did in the past.

Integrated resource management is popularly termed multiple-use (Duerr 1982). Multiple-use is management that intends to produce a set of forest goods and services. Because of the forests' ability and tendency to furnish multiple services, the term multiple-use has been vital to forest managers (Teeguarden 1982).

A central role of the forest manager is decision making, choosing among alternative courses of action (Davis and Johnson 1987). Compared with agriculture, a decision for forest management is more important and more difficult to make. Since the growth period of agricultural crops is no more than one year and the environmental factors are relatively easier to control, a farmer's decision or plan is not difficult to make and modify with each growing period. On the other hand, trees need several decades or more than a hundred years to become mature and the forest environment is much more complex both in species competition and the changes in structure that occur over time. Therefore, it is difficult for a forest manager to make a proper decision for the multiple-use of forest resources.

LEGISLATION OF THE MULTIPLE-USE POLICY

In the United States, the multiple-use concept was developed in the early 1940s, and formed the basis for the later passage of the Multiple-Use and Sustained-Yield Act of 1960 (MUSY Act). This act explicitly listed objectives of multiple-use management (Bowes and Krutilla 1989). With the MUSY Act, the USDA Forest Service was charged with the administrative policy of managing the national forests for various compatible uses in perpetuity. Later on, the US congress successively passed the Wilderness Act and the National Environmental Policy Act (NEPA) in 1969, the Resource Planning Act (RPA) in 1974, and the National Forest Management Act (NFMA) in 1976 (Franzese 1988). The legislation further changed the scope and dramatically increased the complexity of planning on federal lands. Under the legislation, the Forest Service assumed the obligation of multiple-use planning and management of national forest resources.

In Canada, since the provinces have jurisdiction and powers in the field of planning and the administration of natural resources, the Parliament of Ontario passed the Conservation Authorities Act (CAC) in 1946 (Higgs 1977). A multiple-use approach to resource management is a fundamental principle embodied in the CAC, a principle that is essential if competing uses for land, forest water, fish, and wildlife are to be satisfied in a rational way (Higgs 1985). The Crown Timber Act grants the minister of Natural Resources in Ontario with the following authority:" for the purpose of forest management, watershed protection, fire protection, or the preservation of beauty of landscape, game preserves or game shelters, direct the marking of trees to be left standing or to be cut in any area designated by him." (Government of Ontario 1990). Under this Act, the Ontario Ministry of Natural Resources (OMNR) maintains control and responsibility over the implementation of timber management through its approval of all timber management plans.

As the general public showed increasing concern over the environmental problems, multiple-use became the essential guide in OMNR's planning policy of forest resource management, as can be seen in its documents (OMNR, 1974, 1977, 1982, 1983, 1988). For administrative regions and districts of the province, land use guidelines have been prepared. The guidelines describe the competing and conflicting uses of forest resources, which are expected to be resolved through multiple-use resource management (OMNR 1982, 1983).

In Direction'90s, the OMNR (1991) presented a new set of goals and objectives to guide the development of policies and programs for resource management in the 1990s. The new goal of the OMNR is "to contribute to the environmental, social and economic well-being of Ontario through the sustainable development of natural resources". Compared with its 1984's goal of " providing opportunities for continuous economic and social benefits to the people of Ontario through the development and conservation of Ontario's natural resources", the OMNR emphasizes the environmental health and sustainability for the management of the natural resources in its new goal. As the views on how to use the natural resources change, the implementation of multiple-use of forest resources will have legislative effects on the resource managers.

PROBLEM SELECTION

Forest management is the art and science of making decisions with regard to the organization, use, and conservation of forests (Buongiorno and Gilless 1987). The integrated forest resource management is a complex process that may often involve attempts to meet competing or conflicting objectives. The development of computer science helps the decision-maker to solve such complex problems. With the aid of the computer, mathematical models have been widely used by researchers who deal with the multiple-use of forest resources. But however useful the models, their use is not as popular in Northwestern Ontario as in the United States. Very few reports have been found using mathematical models to resolve multiple-use problems in this region. The situation does not conform to the principles of sustainable development of forest resources in the 1990s issued by the OMNR.

This study, by combining two mathematical models, attempts to make an integrated resource management plan for a specific area in Northwestern Ontario. Based on scientific merit, available information, and timeliness, timber, wildlife (represented by moose, Alces alces) and forest aesthetics were selected as three response variables in the model.

OBJECTIVE

The primary objective of this study was to develop mathematical models with existing computer programs and to use these models to assist in providing useful information for multiple-use planning in a case study area. To accomplish this objective, the following specific questions were answered:

1) How can the goal programming (GP) and the STELLA[1] models be formulated for multiple-use planning? How can variables be introduced into the model?

2) How can the non-timber variables (wildlife, aesthetics) be dealt with in the model?

3) Is it possible to set goal target levels for the GP model by using the STELLA model solution?

4) Is it possible to make the models represent changes of forests over time?

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1. STELLA - Structural Thinking, Experiential Learning Laboratory with Animation

LITERATURE REVIEW

As multiple-use of forest resources has become an important issue to our society, a great deal of effort has been made in studying the various uses of forest resources, such as wildlife, recreation, aesthetics, environmental protection, etc. Those studies mainly deal with two problems:

1) The controllable or measurable factors that influence the uses or services of forests have been investigated on the assumption that the potential of those services could be measured or predicted.

2) The technology of evaluating the goods and services of forests from an economic point of view has been studied so that the conflicts between forest services could be analyzed on the level of trade-off among competing uses. The result of this analysis could show forest managers the gains and benefits forgone.

Although most of those studies deal with one variable each time, i. e. different researchers conduct their studies on one topic (wildlife, recreation, forest aesthetics, etc.), the results and experiences from those studies have made great contributions to integrated forest resource management. Indeed, most decisions for multiple-use of forest resources are made by using experiences and information from those studies (Calish *et al.* 1978). This chapter reviews the knowledge of research on wildlife (represented by moose) and forest aesthetics, and the theory and application of two mathematical models, namely, system dynamic (SD) and goal programming (GP) models, which were used in this study.

MOOSE

According to Schwartz and Franzmann (1989), wildlife populations respond to a number of factors which tend to decrease population size (i.e. predation, disease, habitat, hunting, and weather). Among these factors, habitat requirements aroused the interests of many moose researchers. It is recognized that populations of moose with abundant food of sufficient quality interspersed with a suitable amount and quality of cover have potential to increase or stabilize at relatively high density in the absence of other factors that contribute to mortality (Allen *et al.* 1987).

Various studies have been undertaken to determine moose browse preference and availability. Summer browse was found to be of higher quality and quantity than winter browse (Renecker and Hudson 1985), but the availability of sufficient winter browse is critical to moose survival (Todesco and Cumming 1985; Crete 1988). A low winter browse density means more walking to find food. This results in a higher energy demand and a general weakening of their condition, especially in deep snow (Vivas and Saether 1987;

Timmermann and McNicol 1988; White 1983). Cumming (1987) summarized the result of 16 years of moose browse survey in Ontario. In his study, twenty-two of 33 recorded plant species were browsed by moose, but only 10 species had browse intensity greater than 1 percent of total browse units, and those 10 species were also ranked in order based on preference and availability. The density, variety and quality of browse is higher on areas disturbed between 5 and 20 years ago (Telfer 1974; Allen *et al.* 1987). Dodds (1974) found that in the areas of 9 to 17 years after logging there was three or four times as much browse as in the mature forests. The estimated carrying capacity of the 17 year-old logged areas was 6.8 ha per moose. The recognized way of estimating the potential of moose production is to examine the available browse in winter (Spencer and Hakala 1964; Oldemeyer *et al.* 1977; Stelfox *et al.* 1976; Schwartz and Franzmann 1989). Schwartz and Franzmann (1989) compared moose population dynamics in one older and one recent burn stand from 1978 to 1988. They found that the relationship of moose density and forest succession in the two areas was following the same pattern, and the high density of moose population was regulated by the habitat quality and quantity. Food shortages limit moose populations at the low levels of availability in mature forests (Cumming 1987).

Moose have specific cover needs in summer and winter. In the summer, moose are sensitive to heat stress and need a place to escape this heat. Cool moist places such as lowland swamps or deciduous stands near water are frequented during hot weather

(Timmermann and McNicol 1988). In the winter, cover needs are different. Moose can withstand extremely cold temperatures (Renecker *et al.* 1978), so the heat retentive capacity of winter cover is not so important although it helps. Moose are more restricted by snow depth, especially in the late winter when snow has accumulated to its maximum depth and is often crusty making travelling difficult. Also at this time of year moose energy reserves are nearly exhausted, so late winter cover appears to be more limiting and critical to moose survival than early winter cover (Timmermann and McNicol 1988). Allen *et al.* (1987), after reviewing available literature and conducting a moose workshop with leading moose specialists, concluded that ideal late winter cover would comprise coniferous tree canopy closure greater than 75 percent and a stand height more than 10.6 m. In the late winter, accessibility of browse to the cut-over area is determined by the distance from cover. Declining trends in browse used by moose were evident with increasing distance from cover in Ontario (Hamilton *et al.* 1980). It is assumed that browse within 100 m of winter cover is indicative of optimum interspersion of dormant-season browse and cover (Allen *et al.* 1987).

The quality of moose habitat is closely related to timber management. Logging, as well as natural phenomena like fire, has been thought to be beneficial to the moose habitat (Welsh 1980; Schwartz and Franzmann 1989; Cumming 1987). Baskerville (1985) pointed out that forest stand dynamics could be used to define optimum moose habitat values in much the same way as timber values and suggested that 'yield' curves for food values, cover values and other such moose habitat indicators be used to predict potential habitat changes for any given harvest and treatment schedule.

FOREST AESTHETICS

Increasing forest recreation activities require forest managers to pay attention to environmental amenities. Since 1970 there has been a great surge of empirical research investigating public perceptions of landscape scenery (Zube *et al.* 1982). Methods developed to assess scenic beauty are either descriptive inventory or preference evaluations (Methven 1974; Craik 1972; Daniel and Boster 1976; Hull *et al.* 1984). Descriptive methods try to develop description-determined numeric beauty indices to quantify forest beauty in a manner like that of other forest outputs, but with less success due to the difficulty of reliable application, interval scaling, and validation (Ribe 1989). A descriptive yet formal procedural approach has been adopted by the USDA Forest Service in its visual system (USDA 1974) at an extensive landscape scale. This system determines the goals of site-specific management prescriptions for areas according to their assessed scenic value and user sensitivities. Similar methods have been used in Canada (Dearden 1983).

Another method is called perceptual preference assessment. It applies psychophysical methods to generate standardized measures of scenic beauty across respondents' differing judgments of forest areas (Buhyoff *et al.* 1986). The scenic beauty estimation (SBE) method, developed by Daniel and Boster (1976) and applied initially to forest scenery, is arguably the most sophisticated method in the field of scenic landscape assessment (Ribe 1989). It has come to be used in many forest perception research studies sponsored by the USDA Forest Service.

A number of researchers (e.g. Arthur 1977; Brown and Daniel 1984; Buhyoff *et al.* 1986; Schroeder and Daniel 1981; Vodak *et al.* 1985) sought to assign public validated and reliable scenic output values to potential local forest conditions for stand level multiple-use management decisions. The more sophisticated preference research projects typically employ regression models using forest characteristics to predict SBE values. From the models developed by the above mentioned investigators, the following conclusions could be made :

(1) Large size trees contribute to positive aesthetic value in a forest landscape. This implies that the stand age is an important factor in predicting SBE values.

(2) Grass vegetation contributes to scenic beauty.

(3) Trees of small size have negative aesthetic value in the opinion of most researchers, but Buhyoff *et al.* (1986) found the scenically optimal number of small trees per ha to be about 2842. That means that the low aesthetic value of the young trees could be explained by their high density. Also, according to Vodak *et al.* (1985), trees of all sizes in hardwood stands were positively related to scenic

beauty. Similarly, Schroeder and Daniel (1981) only considered small coniferous trees to provide negative scenic value and hardwood trees of all sizes to have a positive value.

(4) Slash in a forest is an important factor in estimating SBE value, and it detracts from scenic beauty.

There are some other studies about public preference of the forest landscape. In the western US, unmanaged forest scenery was preferred when compared to intensively managed, recently harvested, or heavily thinned areas (Daniel and Boster 1976). Old-growth lodgepole pine (Pinus contorta Dougl.), douglas fir (Pseudotsuga menziesii (Mirb.) Franco), and larch (Larix spp Mill.) forests were highly preferred over recently harvested scenes from the same forest types (Benson and Ullrich 1981; Schweitzer *et al.* 1976).

Two reported findings relate scenic beauty explicitly to forests' age structure. In one, mature even-aged ponderosa pine (Pinus ponderosa Laws.) stands were preferred to uneven-aged stands, which were preferred to the young even-aged stands (Brown and Daniel 1984). In the other, the perceived beauty of even-aged loblolly pine (Pinus taeda L.) stands grew with age (Hull and Buhyoff 1986). It was assumed that scenic beauty up to age 11 behaves according to the following logarithmic structure:

$$SBE = a + b\ln(age) + age$$

The constant, b, was set so that scenic beauty of the stand at age 11 equaled the scenic beauty predicted by the scenic simulator at age 11; the intercept , a, was set to equal the scenic beauty which was determined by averaging scenic beauty values associated with recently clear-cut stands. Scenic beauty, therefore, was assumed to be at its minimum immediately following harvest and was expected to increase rapidly as the clear-cut area covered with new growth.

These past research efforts show that scenic beauty of the forest environment can be assessed and predicted by forest characteristics subject to management (Hull and Buhyoff 1986). Forest managers should take the effects of timber harvesting on scenic beauty into consideration. Clear-cut areas are considered to have severe effects on forest landscape (Routledge and Forshed 1981). Some special consideration should be given to sensitive areas, such as roadside, water-body side, etc. (Sloan 1986; OMNR nd). Mcree (1970) suggested that the adverse reaction to clear-cutting can be reduced by implementing a number of procedures, most of which will be costly, but timber producing interests must be willing to contribute more towards maintaining a high-quality environment and protecting the beauty of the forest.

MATHEMATICAL MODELS

System Dynamic Model (SD)

System Approach

A system may be defined as a collection of interacting elements that function together for some purpose (Roberts *et al.* 1983). Wiener (1948) first named and sketched the outlines of a new field of inquiry, Cybernetics, which became the study of how biological, engineering, social, and economic systems are controlled and regulated. Forrester (1961) first applied the broad principles of cybernetics to industrial systems. Forrester's initial work in industrial systems has been subsequently broadened to include other social and economic systems and is known as the field of system dynamics. Based on Forrester's work, Roberts *et al.* (1983) presented the simulation modelling techniques. Relying heavily on the computer, system dynamics provide a framework in which to apply the idea of system theory to problems in many fields.

Structure And Simulation of The SD Model

According to Roberts *et al.* (1983), there are three critical aspects of the system dynamic approach to developing computer simulation models:

(1) Causation. Causal thinking is the key to organizing ideas in a system dynamic study. Key causal factors should be isolated and the system of causal relationships diagrammed, so called causal chains, before a computer simulation model is built.

(2) Feedback. Circular causal chains are called causal loops. Within a causal loop, an initial cause ripples through the entire chain of causes and effects until the initial cause eventually becomes an indirect effect of itself.

(3) System boundary. A system boundary is the complex process of defining the size, scope, and character of the problem being studied.

A simple causal loop is the basic unit in building the diagram of a system dynamic model. The causal loop can be regarded as a feedback system. As shown in Figure 1, as the number of seeds increase, the number of trees increase, the increased trees in return produce more seeds. It is called positive feedback loop, as indicated by a 'U-turn' sign. A negative feedback loop can be seen in Figure 2, harvesting causes the number of trees to decrease. Negative loops seek to maintain the balance of the system (Roberts *et al.* 1983). A system dynamic diagram is developed by linking many such feedback loops. Once a flow diagram has been developed, the next step is to write equations by using the dynamic model (DYNAMO) simulation language. The models can then be analyzed and modified during the simulation.

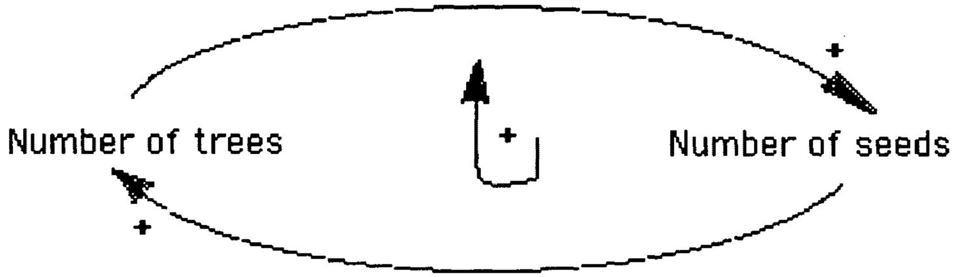

Figure 1. The positive causal loops between trees and seeds (from Robert *et al.* 1983)

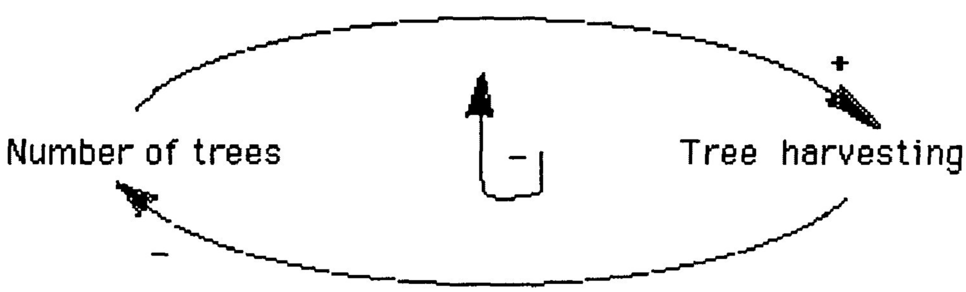

Figure 2. The negative causal loops between trees and harvesting (from Robert *et al.* 1983)

Application of The SD Model in Forest Management

So far, only a few projects have applied SD models to forest management. Ung *et al.* (1978) developed a system dynamic model to test the effects of silviculture activities on the growth of black spruce. Boyce (1977, 1978) described the technique of management of forests for multiple benefits. Ågren (1987) introduced system dynamic models in his work, Models for Forestry. Among them, Boyce's work seems the most valuable to mention. His approach is to classify the forest land into several different habitats (Figure 3).

The model has a cybernetic structure, the distribution of habitats in the forest is being changed by the harvest of timber and forest succession. Boyce (1978) pointed out that the model was arranged to guide the forest toward a goal through a set of negative feedback loops. The goal is to achieve a given distribution of habitats and maintain it in a steady state. The multiple benefits can then be estimated by constructing the relationship between habitats and requirements of each benefit; the relationship is expressed as an index. With an SD model, any behaviour or response of the forest can be visualized graphically (Ung *et al.* 1978), and some more variables can easily be added to the model without causing much extra work (Boyce 1978). But since the formulation of a model was based completely on past experience and knowledge, and environmental factors were not taken into consideration, such as

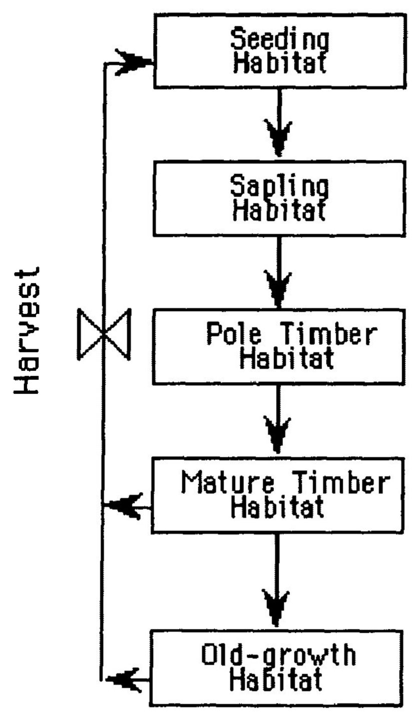

Figure 3. A simplification of the system dynamic model (from Boyce 1977)

site class, species composition, etc., the results from the model can only give the forest manager a general idea on how to manage the forest The model cannot make a specific management plan.

Goal Programming Model (GP)

Goal Programming Formulation

GP is a modification of linear programming (Field 1973). Charnes and Cooper (1961) first developed this programming formulation. A primal linear programming model focuses on the program of determining an optimal allocation of resources to meet a given set of objectives. GP, in a similar format, seeks a plan that comes as close as possible to attaining specific goals.

The objective function of GP is to minimize deviations from multiple goals, which are added as a set of constraints with deviations. The general GP model can be formulated as follows:

Minimize $Z = WD^{+} + WD^{-}$

subject to

$$AX - D^{+} + D^{-} = G$$

$$CX \leq B$$

$X, D^+, D^- \geq 0$

where:

Z	total deviation;
W	1 * m vector of weighted or unweighted priority factors;
D^-, D^+ -	m * 1 vectors representing, respectively, positive and negative deviations from goals;
A	m * n matrix of decision variable weights;
X	n * 1 vector of decision variables ;
G	m * 1 vector of goal target levels;
C	p * n matrix of technological coefficients;
B	p * 1 vector of available resource amounts .

The basic idea of GP is to establish a specific numerical goal for each objective, to formulate a function for each objective, and then to seek a solution that minimizes the weighted sum of deviations of these objective functions from their respective goals.

Application to The Problems of Natural Resource Management

Since Field (1973) first discussed GP for forest management, researchers have made impressive progress in applying it in this field. They have described how the technique can be applied to a variety of forestry problems such as land-use planning (Bell 1976; Dane *et al.* 1977; Arp and Lavigne 1982), timber harvest scheduling (Rustagi 1976; Kao and Brodie 1979), multiple-use forestry (Schuler and Meadows 1975; Steuer and Schuler 1979; Chang and

Buongiorno 1981), design of forest inventory (Mitchell and Bare 1981), and range management (Bottoms and Bartlett 1975).

The discussion here will focus on how GP has been applied to natural resource management problems in the context of multiple-use and how the variables, especially non-timber benefits, are approached and introduced in the GP model.

The objectives most frequently dealt with are timber production, wildlife, and outdoor recreation.

1. Timber production objective

Since timber production of forests is relatively easy to estimate, its goal can be clearly set in the model. Schuler and Meadows (1975) used saw timber and pulpwood of hardwood and softwood as goals. Dane *et al.* (1977), and Arp and Lavigne (1982) set merchantable volume goals. The harvest area could also serve as a timber management goal (Chang and Buongiorno 1981). Bottoms and Bartlett (1975) set their timber goals by using specific species volumes.

2. Wildlife management objective

Arp and Lavigne (1982) chose deer population level as goal. Other authors (Schuler and Meadows 1975; Bell 1976; Dane 1977; Bottoms and Bartlett 1975; Steuer and Schuler 1979) used grazing availability as goals.

3. Outdoor recreation management objective

Each author (Arp and Lavigne 1982; Chang and Buongiorno 1981; Schuler and Meadows 1975; Bell 1976; Dane 1977; Bottoms and Bartlett 1975; Steuer and Schuler 1979) selected one or more outdoor recreation activities as goals, such as dispersed recreation (hiking, snow-shoeing, cross-country skiing, and interpretive walks, etc), developed recreation (picnicking, camping, etc.), and hunting. They all used visitor day or hunter-day as a unit of measure for the goals.

Though GP has been a powerful and useful tool for multiple-use planning, there are still some problems for the decision-maker to deal with:

(1) All the goal targets have to be preset as constraints to the objective function. A set of reasonable target levels will give better and meaningful GP solutions. But the decision maker is often unable to specify the targets due to lack of sufficient knowledge of the decision environment (Mendoza 1985).

(2) The most difficult part in applying mathematical models to integrated forest management is that it lacks reliable data for non-timber products. So most researchers resort to making estimates about these products or services, such as wildlife and recreation. As the estimates were made based on past experience and knowledge, they are somewhat abstract and arbitrary. Also, using only one factor to estimate some non-timber outputs does not always reflect the real situation; for example, the factors which influence wildlife

(such as moose) are not only food availability, but thermal cover, predation, hunting pressure, etc.

Combining The SD And GP Models

As shown above, neither SD nor GP is perfect model. Each has strong and weak points. In order to deal with the complicated problems in integrated forest resource management, it may be necessary to combine the two models in the land-use planning program. The SD model treats the forest in a dynamic manner, and it can help the resource manager to envisage the problem in a wider context than the GP model. Also, the SD model can guide decision-makers to set more reasonable and practical target levels for the GP model. Therefore, the solution of goal models may be improved and become more suitable to a real situation. Combining the two models may enable complex resource management problems to be handled more effectively than employing only one of the models.

MODEL FORMULATION AND APPROACH

This chapter will discuss the procedures of formulating the system dynamic model. The modelling approach (both SD and GP model) will also be discussed. In this study, a system dynamic model software, STELLA (Richmond *et al.* 1987), was used for formulating and running the model.

STELLA MODEL

The concept and design of the STELLA model developed for the study was inspired by the model constructed by Boyce (1977) to simulate eastern hardwood forests in the United States. He attempted to establish long-term strategies for forest resource utilization. From his prototype, I designed a model to be used in this study.

First, the forest stands were classified into age-classes. The terms, seedling habitat (SE), mature timber habitat reserves (MTR) and old-growth reserves (OGR) were used for corresponding age-classes. The time intervals for mature and old-growth habitats were determined according to a certain management policy.

The Central Model for Succession And Harvest

The model contains a set of negative feedback loops with the goal of converting the current distribution of age-classes to the desired distribution and maintaining the desired distribution at a steady state (Boyce 1977). This was achieved by using harvest rates for old-growth and mature timber to control formation of seedling habitat.

The structure of the feedback loops is illustrated in a flow diagram of the information network (Appendix 1). Arrows show the flow direction of information. Single lines indicate a flow of information about the state of the inventory and other parts of the system. Double lines indicate a flow of information about changes in the inventory resulting from harvest and succession of age-classes. Symbols in the diagram (rectangles, "valves", and single circles) indicate, respectively: level, rate, and auxiliary equations. The model automatically writes an equation for a level when an initial (INIT) value is entered. The rate and auxiliary equations can be a constant or a mathematical formula. A graph of the relationship between two variables may be used instead of an equation.

In order to demonstrate how the model works, a part of the model is used as an example (Figure 4). Three rectangles, two valves, and two circles in Figure 4A indicate respectively: age-classes, succession rates, and delay of succession. AGE30, AGE50,

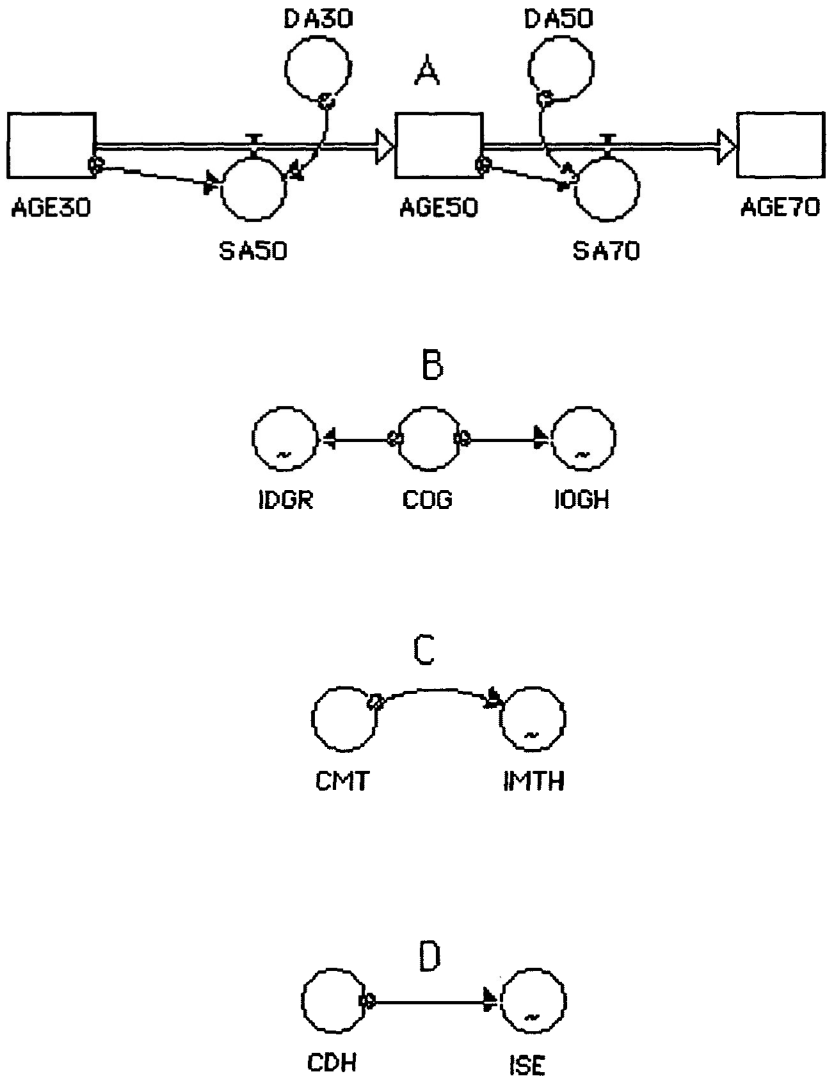

Figure 4. Component parts of the STELLA model

and AGE70 (the levels) are areas in age-classes 21-40, 41-60, and 61-80 years respectively. SA50 and SA70 (the valves) are succession rates from age-class 21-40 to age-class 41-60, and from age-class 41-60 to age-class 61-80, respectively. DA30 and DA50 (the circles) are years of delay for succession to the next age-class. Every symbol in Figure 4A refers to an equation or a constant. The equations for each symbol in Figure 4A are as follows:

$$AGE30 = AGE30 + dt * (SA15 - SA30) \quad (1)$$
$$INIT(AGE30) = 165$$
$$AGE50 = AGE50 + dt * (SA50 - SA70) \quad (2)$$
$$INIT(AGE50) = 84$$
$$AGE70 = AGE70 + dt * (SA70 - SMT) \quad (3)$$
$$INIT(AGE70) = 560$$
$$SA50 = AGE30/DA30 \quad (4)$$
$$SA70 = AGE50/DA50 \quad (5)$$
$$DA30 = 20 \quad (6)$$
$$DA50 = 20 \quad (7)$$

where:

AGE30 - Area in age-class 21-40 years (ha)
AGE50 - Area in age-class 41-60 years (ha)
AGE70 - Area in age-class 61-80 years (ha)
DA30 - Delay for age-class 21-40 succession (years)
DA50 - Delay for age-class 41-60 succession (years)
SA50 - Succession to age-class 41-60 (ha/year)
SA70 - Succession to age-class 61-80 (ha/year)
INIT - Initial area (ha)
dt - Delta time (one year).

In the same way, an equation can be written for every symbol in the model (Appendix 1). Once all the equations were completed, the model was in a running state. As the model runs, the values of age-classes and succession rates change at every simulation step (dt) until the model reaches a steady state.

The model determined harvest by sensing the current distribution of habitats, comparing it with a desired distribution, and then computing the rates of harvest. The inventory of the current distribution of habitat in the forest provided the initial area of the habitat in the model. Successive areas of habitats were computed by integration

A desired distribution of habitats was determined by following Boyce's method (1977). In the central model (Appendix 1), four equations were replaced by graphs, which were used to calculate a desired distribution of habitats. Figures 4B, C, and D show the relationships of variables graphically. The three independent variables are called coverage of old-growth reserves (COG) (Figure 4B), coverage of mature timber reserves (CMT) (Figure 4C), and coverage of seedling habitat (CDH) (Figure 4D). The equations for calculating the three variables are as follows:

$$COG = OGR/EOG \qquad (8)$$

$$CMT = MTR/EMT \qquad (9)$$

$$CDH = SE/EDH \qquad (10)$$

where:

COG - Coverage of old-growth reserves (dimensionless)

OGR - Area of old-growth reserves (ha)

EOG - Area of equilibrium old-growth habitat (ha)

CMT - Coverage of mature timber reserves (dimensionless)

MTR - Mature timber reserves (ha)

EMT - Equilibrium mature habitat (ha)

CDH - Coverage of seedling habitat (dimensionless)

SE - Area of seedling habitat (ha)

EDH - Equilibrium seedling habitat (ha)

Equilibrium habitat is a theoretical area of a habitat when the forest is in a normal state. The equations for calculating EOG, EMT, and EDH are listed below.

$$EOG = FOG * DOG \quad (11)$$

$$EMT = (FMT+FOG) * DMT \quad (12)$$

$$EDH = (FOG + FMT) * DSE \quad (13)$$

where:

FOG - Flow rate of old-growth reserves (ha/year)

DOG - Delay of old-growth succession (years)

FMT - Flow rate of mature timber reserves (ha/year)

DMT - Delay of mature habitat succession (years)

DSE - Delay of seedling habitat succession (years)

The calculation of FOG and FMT will be discussed later. From the equations for calculating COG, CMT, and CDH, it is obvious that these three variables are dimensionless. They serve as factors in the model to control four dependent variables, namely: indicated old-growth harvest (IOGH), indicated mature timber harvest (IMTH), indicated old-growth reserves (IOGR), and indicated seedling habitat (ISE). Figure 5 shows that the relationships between COG and IOGH, and between CMT and IMTH are the same. When COG (CMT) is less than or equal to 0.5, IOGH (IMTH) is zero. As COG (CMT) increases, IOGH (IMTH) increases until it reaches 1.3; at this point COG is 2.5. These two indicators are used to calculate mature timber harvest (MTH) and old-growth harvest (OGH) in the model. Figure 6 shows the relationship between CDH and ISE and between COG and IOGR. ISE was used to control mature timber harvest in the model, and IOGR was used to control the succession rate to the old-growth reserves. These four indicators (IOGH, IMTH, IOGR, and ISE) are important parameters. Their uses will be discussed in the following sections.

The Old-growth Feedback Loop

The amount of old-growth harvest (OGH) is a product of the indicated old-growth harvest (IOGH) and the flow rate of old-growth succession (FOG). This flow rate, FOG, represents the areas of old-growth ready for harvesting each year. FOG is determined by multiplying the total area of the forest (TAH) and the old-growth fraction (OGF), divided by the rotation age of the old-growth reserves. Therefore, we have,

$$OGH = IOGH * FOG \qquad (14)$$

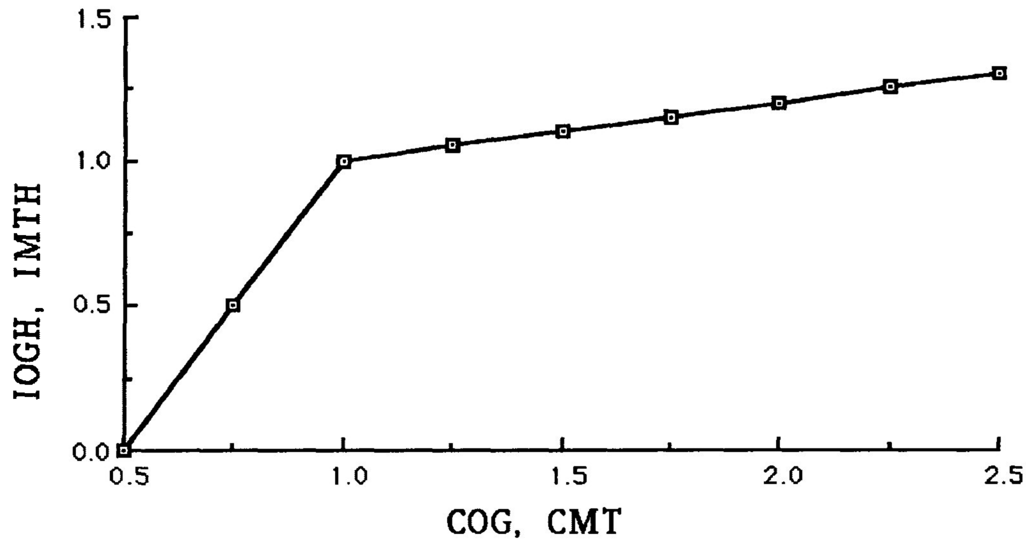

Figure 5. The indicated old-growth harvest (IOGH) and mature timber harvest (IMTH) versus the coverage of old growth (COG) and mature timber habitat (CMT) (from Boyce 1977)

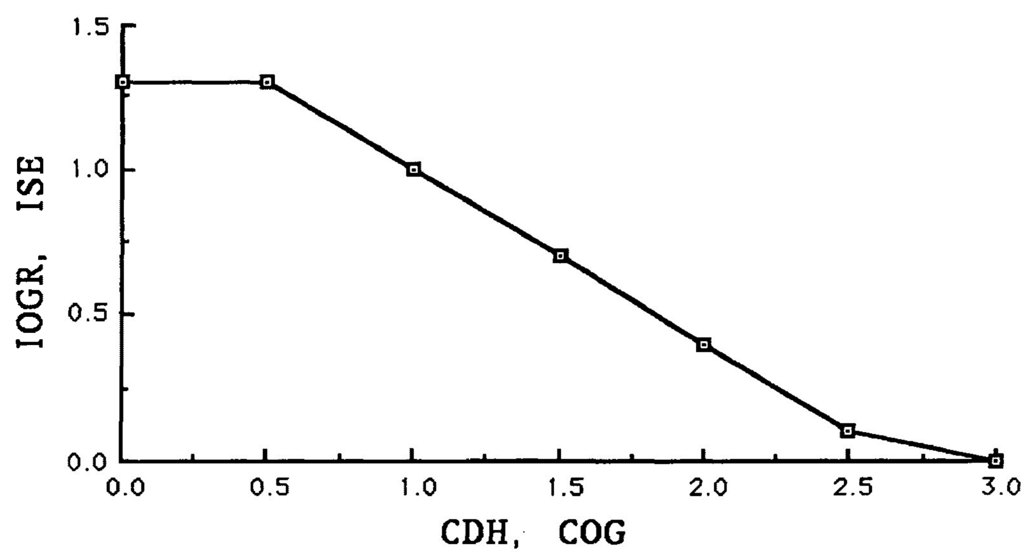

Figure 6. The indicated seedling habitat (ISE) and indicated old-growth reserves (IOGR) versus the coverage of seedling habitat (CDH) and old-growth reserves (COG) (from Boyce 1977)

$$FOG = (TAH * OGF)/(DSE + DA15 + DA30 + DA50 + DA70 + DMT + DOG) \quad (15)$$

$$TAH = SE + AGE15 + AGE30 + AGE50 + AGE70 + MTR + OGR \quad (16)$$

where:

OGH - Old-growth harvest (ha/year)
IOGH - Indicated old-growth harvest (dimensionless)
FOG - Flow rate of old-growth reserves (ha/year)
TAH - Total area of all age-classes and habitats (ha)
OGF - Fraction harvested through old-growth reserves
DSE - Delay for seeding succession (years)
DA15 - Delay for age-class 11-20 years succession (years)
DA30 - Delay for age-class 21-40 years succession (years)
DA50 - Delay for age-class 41-60 years succession (years)
DA70 - Delay for age-class 61-80 years succession (years)
DMT - Delay for mature timber succession (years)
DOG - Delay for old-growth succession (years)
SE - Area of seedling habitat (ha)
AGE15 - Area in age-class 11-20 years (ha)
AGE30 - Area in age-class 21-40 years (ha)
AGE50 - Area in age-class 41-60 years (ha)
AGE70 - Area in age-class 61-80 years (ha)
MTR - Area in mature timber reserves (ha)
OGR - Area in old-growth reserves (ha)

IOGH is controlled by the coverage of old-growth habitat (COG) (Figure 5). It shows that old-growth harvest could be as low as zero, or as high as 1.3 times the flow of old-growth succession (FOG), depending on the changes of COG (Figure 5).

The Mature Timber Feedback Loop

Three variables, ISE, IMTH, and FMT, are used to determine the mature timber harvest (MTH), where ISE is the amount of harvest needed to maintain seedling habitat, IMTH is indicated mature timber harvest, and FMT is the flow rate of mature timber reserves (ha/year). The calculation of mature timber harvest (MTH) is: first, the model selects the smaller indicators of habitat diversion, either ISE or IMTH, and then multiplies it by the flow rate of succession to mature timber habitats (FMT). FMT is the product of total area (TAH) of habitats or age-classes and the designated mature timber fraction, divided by the desired age of harvest. The equation is as follows:

$$MTH = (\min(ISE,\ IMTH)) * FMT \tag{17}$$

$$FMT = (TAH*(1 - OGF)/(DSE+DA15+DA30+DA50+DA70+DMT) \tag{18}$$

where:

MTH - Area of mature timber harvest (ha/year)
ISE - Indicated seedling habitat (dimensionless)
IMTH - Indicated mature timber harvest (dimensionless)
FMT - Flow rate of mature timber reserves (ha/year)
OGF - Fraction harvested through old-growth reserves

In equation 17, the mature timber harvest is also controlled by indicated seedling habitat (ISE), which depends on the changes of the coverage of seedling habitat (CDH) (Figure 6). Figure 6 shows that, when coverage of seedling habitat (CDH) is zero, the harvest increases up to 1.3 times of the flow rate (FMT). When CDH is 1, the harvest is limited to flow rate, FMT. When the coverage is more than 1, the harvest is reduced. In this way, the mature timber harvest is determined by sensing the area of seedling habitat.

The Transfer from Mature Timber to Old-growth

To determine the rate of transfer from mature timber to old-growth reserves (TOG), the model selects the smaller of the two indicators, indicated mature timber harvest (IMTH) or indicated old-growth reserves (IOGR). The smaller indicator is multiplied by the rate of flow of succession to old-growth habitat (FOG).

$$TOG = (\min (IMTH,\ IOGR)) * FOG \qquad (19)$$

where:

TOG - The rate of transfer from mature timber to old-growth reserves (ha/year)

IMTH - Indicated mature timber harvest (dimensionless)

IOGR - Indicated old-growth reserves (dimensionless)

FOG - Flow rate of old-growth reserves (ha/year)

The indicated old-growth reserves (IOGR) is a function of the coverage of old-growth habitat (COG) (Figure 6).

The Flow of Succession

Once the old-growth and mature timber habitats were diverted, the seedling habitat progressed through stages of succession. This process was modelled by the rate ('valve' sign) and level ('rectangle' sign) (Appendix 1). Those two variables defined the state of the system at a given moment. A level was an accumulation at each simulation step (dt), whereas a rate determined the speed at which a level changes.

In the model (Appendix 1), age-classes or habitats were referred to as levels. Each age-class or habitat had an initial value. During the model simulation, the area of age-classes changed at every simulation step (dt). As can be seen in the diagram (Appendix 1), every age-class or habitat has both an inflow and outflow value at the same time. Both are determined by the succession rate (harvesting rate for seedling habitat). The succession rate was determined by the area of age-classes or habitats and the delay of succession. The equations describing the flow of succession are listed in Appendices 2 and 3.

Estimating Benefits

The central STELLA model predicted what distribution of age-classes or habitats would follow from a given management policy. The availability of benefits depended on the state of physical organization of the forest -- the proportions that were covered by different age-classes or habitats. A statement of relationship was constructed to express how a particular benefit depended on the distribution of habitats.

Three supplementary models were established to compute potential indices for three benefits, namely timber, moose and forest aesthetics. The techniques are explained in the following sections.

Timber Potential Index (TPI)

Data on black spruce (Picea mariana (Mill) B.S.P.) were used (Plonski 1974). The relationship between gross merchantable timber yield and forest stand age is shown in Table 1 and Figure 7.

Timber potential index (TPI) is the ratio of the harvest volume based on the STELLA model to the volume harvested under a timber only management policy.

The volume harvested under the timber only management policy was also called timber yield maximum (TYM). It was computed by multiplying the timber yield rate (TYR) by the total area of habitat (TAH) and divided by the rotation age for maximum yield (TMR). This is equivalent to a long term sustainable yield calculation (Davis and Johnson 1987). The following equation was used:

$$TYM = (TAH/TMR) * TYR \qquad (20)$$

where:

TYM - Timber yield maximum (m^3/year)

Table 1. The gross merchantable timber yield for black spruce in Ontario

Age (years)	Periodic annual increment (PAI) (m^3/ha)	Mean annual increment (MAI) (m^3/ha)	Yield[a] (m^3/ha)
60	3.90	1.10	66
80	3.38	1.67	133.5
100	2.95	1.95	195
120	1.90	1.94	233
140	0.98	1.80	252.5
160	0.20	1.60	256.5
180	0	1.43	256.5
200	0	1.28	256.5

Source: Plonski, 1974

a. The average yield between site classes 1 and 2.

Figure 7. Gross merchantable timber yield rate (m^3/ha) versus the age of forest stands

TAH - Total area of all habitats or age-classes (ha)
TMR - Timber yield maximum rotation age (years)
TYR - Timber yield rate (m^3/ha) taken from the yield curve (Figure 7) according to timber maximum rotation age (TMR)

Timber harvested based on the STELLA model included volume from mature habitat reserves (MTR) and old-growth reserves (OGR) (Figure 8). A similar method of calculating the volume for the two habitats was used. First, harvest ages for mature timber (HAMT) and for old timber (HAOG) were calculated. Second, mature timber yield rate (MTYR) and old-growth yield rate (OGYR) were determined. Both MTYR and OGYR were looked up from the timber yield curve (Figure 7) according to the harvest age (HAMT and HAOG). Third, timber volume from mature timber habitat (TVM) and from old-growth reserves (TVO) was computed by using the results from the first two steps. The equations are as follows:

$$HAMT = (MTR/FMT) + 80 \quad (21)$$

$$HAOG = (OGR/FOG) + 80 + DMT \quad (22)$$

where:

HAMT - Harvest age of mature timber (years)
HAOG - Harvest age of old-growth reserves (years)
MTR - The area of mature timber reserves (ha)
FMT - The flow rate of succession to mature timber reserves (ha/year)
80 - Transition age mature (years)
OGR - The area of old-growth reserves (ha)
FOG - The flow rate of succession to old-growth reserves (ha/year)

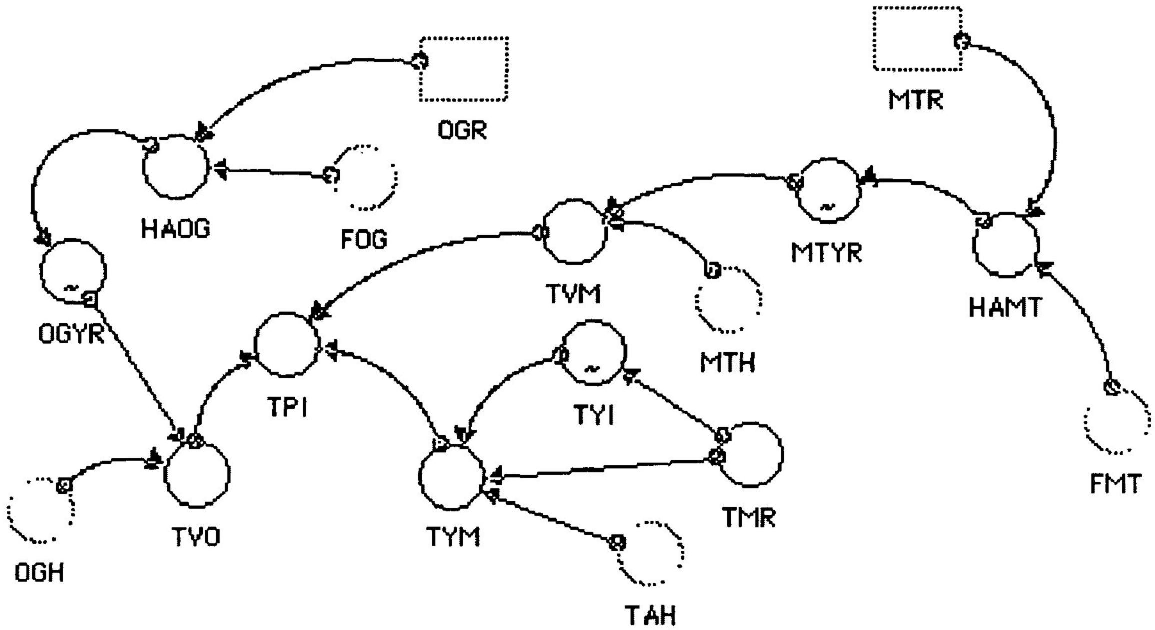

Figure 8. Supplementary model for estimating timber potential index (TPI)

where: **FMT** - The flow rate of succession to mature timber habitat; **FOG** - The flow rate of succession to old-growth reserves; **HAMT** - Harvest age of mature timber; **HAOG** - Harvest age of old-growth reserves; **MTH** - Mature timber harvested; **MTR** - The area of mature timber reserves; **MTYR** - Mature timber yield rate; **OGH** - Old-growth timber harvest; **OGR** - The area of old-growth reserves; **TAH** - Total area of the all habitats; **TMR** - Timber maximum rotation age; **TPI** - Timber potential index; **TVM** - Timber volume from mature timber habitat; **TVO** - Timber volume from old-growth reserves; **TYM** - Timber yield maximum; **TYR** - Timber yield rate based on TMR; **OGYR** - old timber yield rate.

DMT - Delay for mature timber succession (years)

$$TVM = MTH * MTYR \quad (23)$$

$$TVO = OGH * OGYR \quad (24)$$

where:

TVM - Timber volume from mature timber reserves (m^3/year)
MTH - Mature timber harvest (ha/year)
MTYR - Mature timber yield rate (m^3/ha) according to HAMT.
TVO - Timber volume from old-growth reserves (m^3/year)
OGH - Old-growth harvest (ha/year)
OGYR - Old timber yield rate (m^3/ha) according to HAOG

Now, the timber potential index (TPI) could be computed using the following equation,

$$TPI = (TVO + TVM)/TYM \quad (25)$$

where:

TPI - Timber potential index
TVO - Timber volume from old-growth reserves (m^3/year)
TVM - Timber volume from mature timber reserves (m^3/year)
TYM - Timber yield maximum (m^3/year)

Moose Potential Index (MPI)

Allen *et al.* (1987) created a model to estimate a moose suitability index based on information from remote sensing. Four variables were considered to have effects on the quality of moose habitat:

(1) Recent harvested area (< 20 years old). The optimum proportion of this cover type is between 40 and 50 percent of the total area (Figure 9a);

(2) Upland deciduous or mixed area (≥ 20 years old). The optimum proportion of this cover type is between 35 and 55 percent of the total area (Figure 9b);

(3) Spruce or fir forest area (≥ 20 years old). The optimum proportion of spruce or fir area is between 5 and 15 percent of the total area (Figure 9c);

(4) Wet land. The optimum proportion of area in riverine, lacustrine, or plaustrine wetlands is between 5-10 percent (Figure 9d).

The first two variables are sensitive to forest cutting and succession. The proportion of recently cut area is changed following every year's logging operation. Over time, the seedling or young forest (< 20 years) area will gradually transfer to the older forest area (≥ 20 years). Therefore, in this study, the first two variables were used to estimate the moose potential index. Based on the model of Allen *et al.* (1987), a supplementary STELLA model (Figure 10.) was established to estimate a moose potential index (MPI) with the following equation:

$$MPI = (IL20 * IG20)^{1/2} \qquad (26)$$

where:

IL20 = suitability index taken from Figure 9a according to the

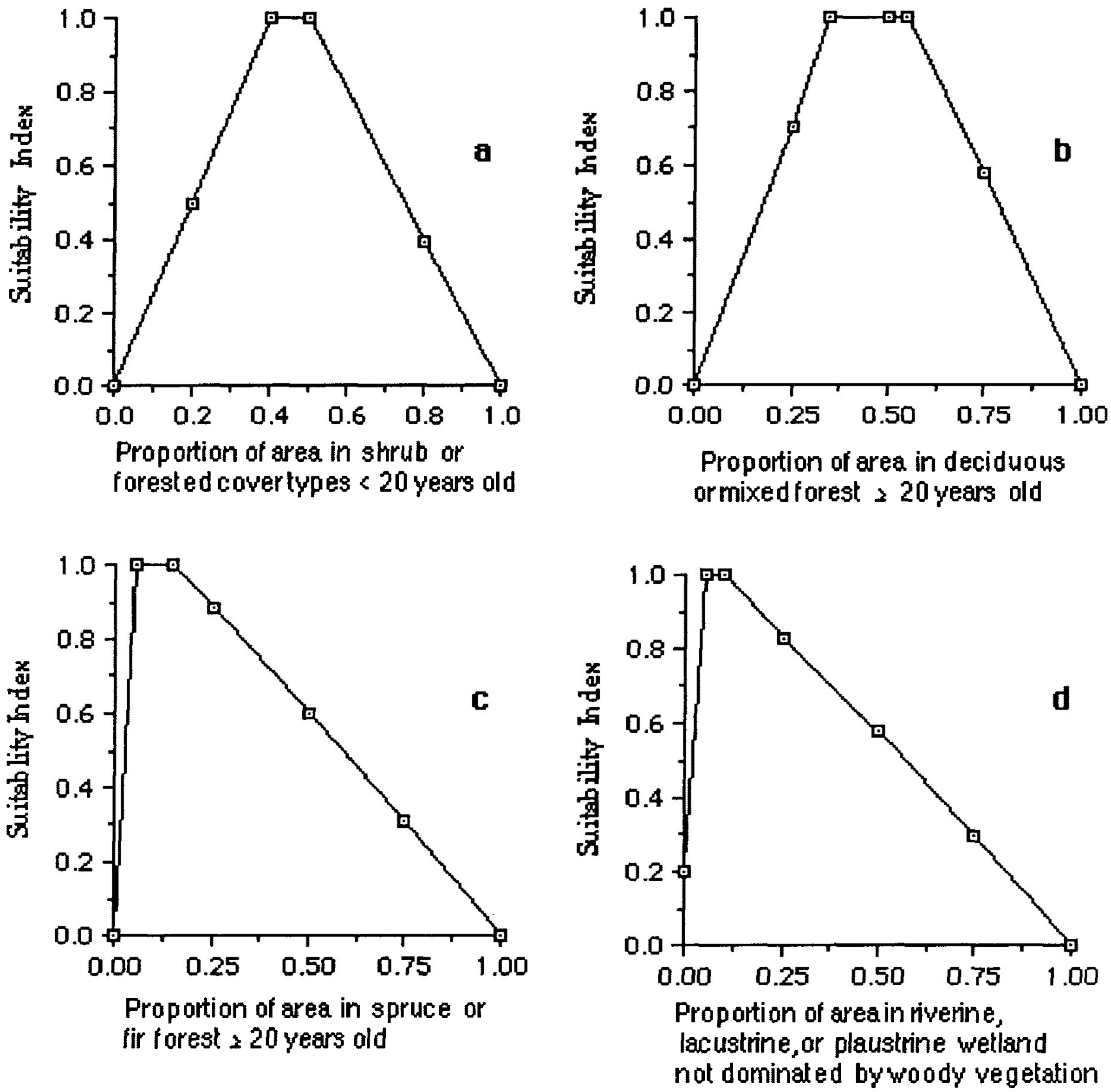

Figure 9. Relationships between variables used to evaluate composition and suitability index values for moose (from Allen *et al.* 1987)

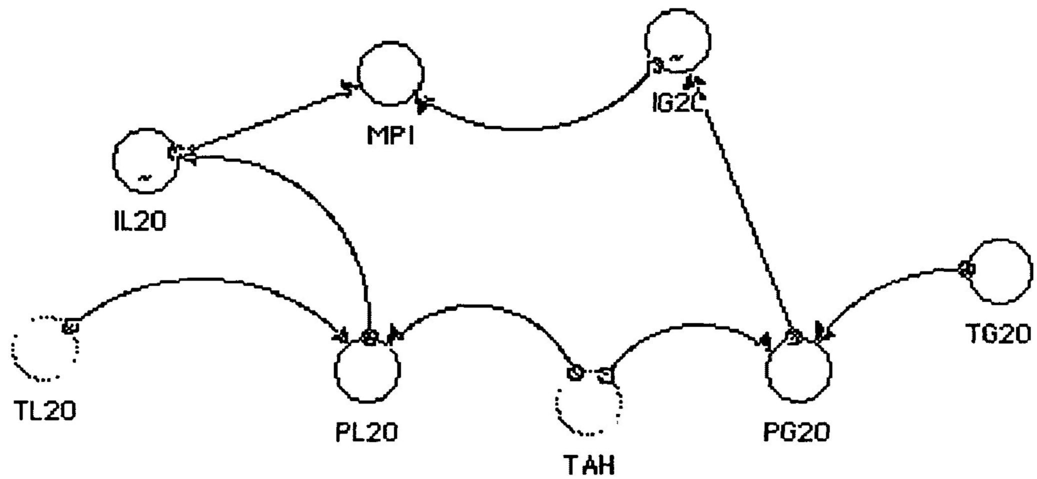

Figure 10. Supplementary STELLA model for estimating moose potential index (MPI)

where: **IG20** - Suitability index based on the proportion of the area of forest stands ≥ 20 years old; **IL20** - Suitability index based on the proportion of area in the stands < 20 years old; **MPI** - Moose potential index; **PG20** - Proportion of the area in stands ≥ 20 years old; **PL20** - Proportion of the area in stands < 20 years old; **TAH** - Total area of all age-classes or habitats; **TG20** - Total area of the stands ≥ 20 years old; **TL20** - Total area of the stands < 20 years old.

proportion of area in shrub or forest cover types < 20 years old (PL20).

IG20 = Suitability index taken from Figure 9b according to the proportion of area in deciduous or mixed forest types (≥ 20 years old) (PG20),

The other two variables in Figure 9 (spruce or fir forest area and wet land) were not used in the model due to two reasons: first, they are assumed to be not so sensitive to forest cutting and succession; second, the changes of these two variables could not be predicted and controlled by the STELLA model.

Aesthetics Potential Index (API)

Figure 11 shows the supplementary STELLA model for estimating an esthetics potential index (API). The model is established following methods used by Boyce (1977). The contrast in height of timber stands is the main variable to evaluate forest aesthetics. The black spruce stands were classified into three height classes, that is, old-growth reserves (OGR), stands over 12 m high, and stands below 12 m high. An optimal situation appears when the three height classes are in balance, with each occupying 30 to 40 percent of the area.

When the proportion of the area in OGR (POG) is about 30 percent, the visual appeal index (VPOG) is 1 (Figure 12). When POG is lower or higher than 30 percent, VPOG declines. Aesthetic value

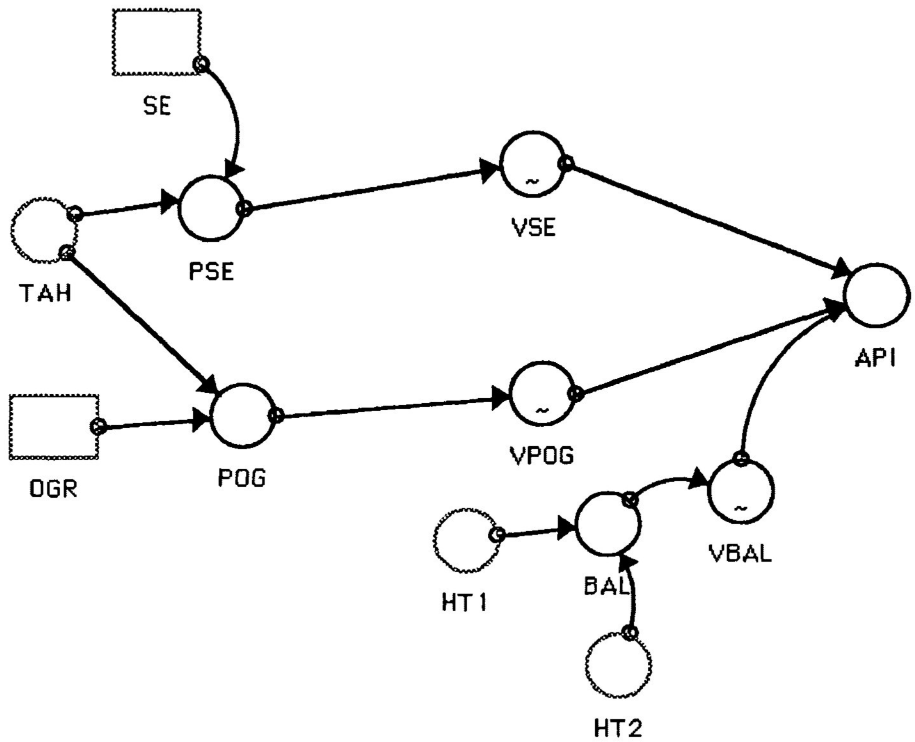

Figure 11. Supplementary STELLA model for estimating aesthetics potential index (API)

where: **API** - Aesthetics potential index; **BAL** - Balance of the area between two height classes; **HT1** - Total area of stands less than 12 m high; **HT2** - Total area of the stands more than 12 m high; **OGR** - The area of old-growth reserves; **POG** - proportion of the area in old-growth reserves; **PSE** - Proportion of the area in seedling habitats; **SE** - the area of seedling habitat; **TAH** - Total area of all the stands; **VBAL** -Visual appeal index based on the BAL; **VPOG** - Visual appeal index based on the POG; **VSE** - Visual appeal index based on the PSE.

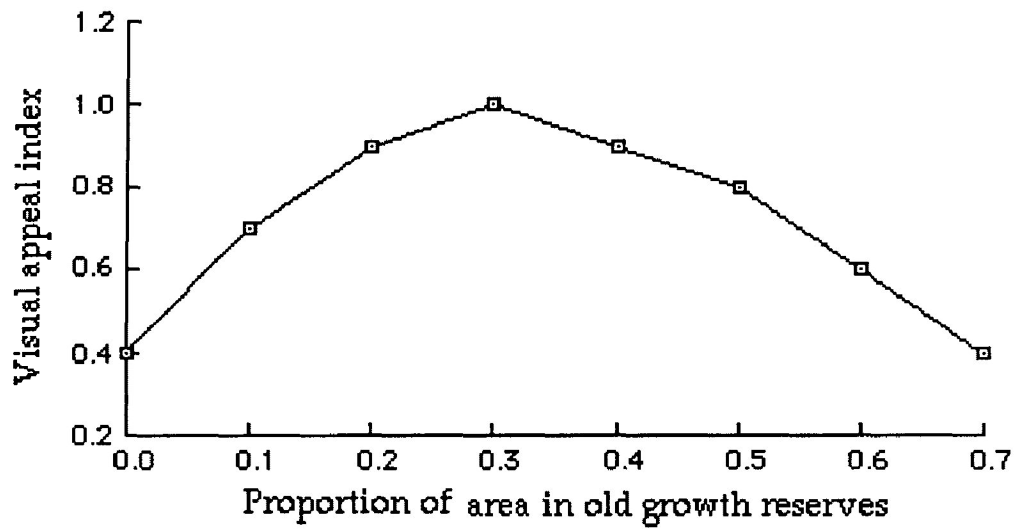

Figure 12. Visual appeal index related to the proportion of area in old-growth reserves (from Boyce 1977)

influenced by the other two height classes is measured by the balance of the two height classes. Visual appeal index (VBAL) rises to 1 when the two height classes are in exact balance (BAL) (Figure 13).

Seedling habitat is also important in estimating the aesthetics potential index (API). The visual index (VSE) is 1 when the proportion of the area in seedling habitat (PSE) equals to 10 percent (Figure 14). As PSE increases or decreases, VSE declines (Figure 14).

The equation for computing aesthetics potential index (API) is as follows:

$$API = VPOG * VBAL * VSE \tag{27}$$

where:

API - Aesthetics potential index

VPOG - Visual appeal index taken from Figure 12 according to the proportion of the area in old-growth habitat

VBAL - Visual appeal index taken from Figure 13 according to the balance (BAL) between two height classes (HT1 and HT2 Figure 11)

VSE - Visual appeal index taken from Figure 14 according to the proportion of area in seedling habitat.

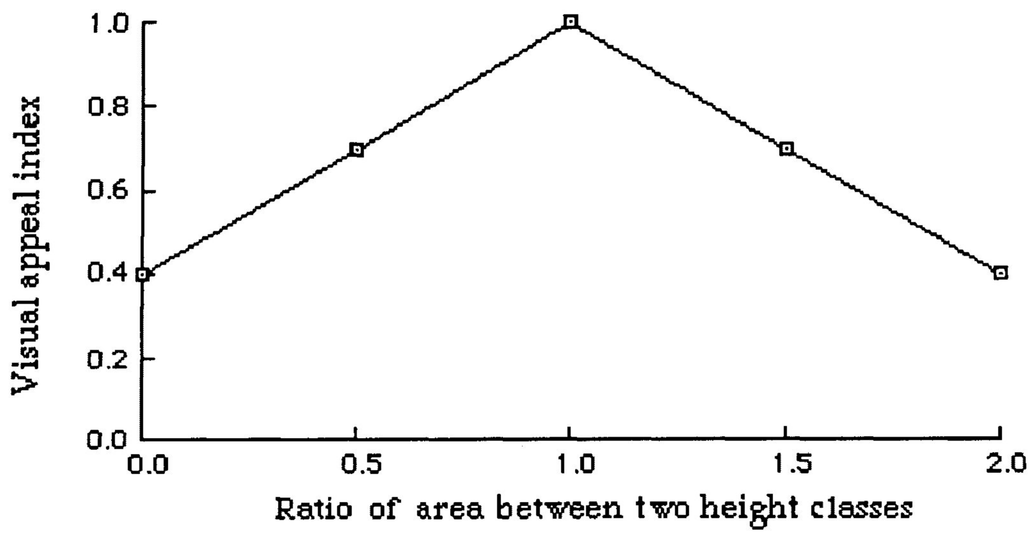

Figure 13. Visual appeal index related to the balance of two height classes (from Boyce 1977)

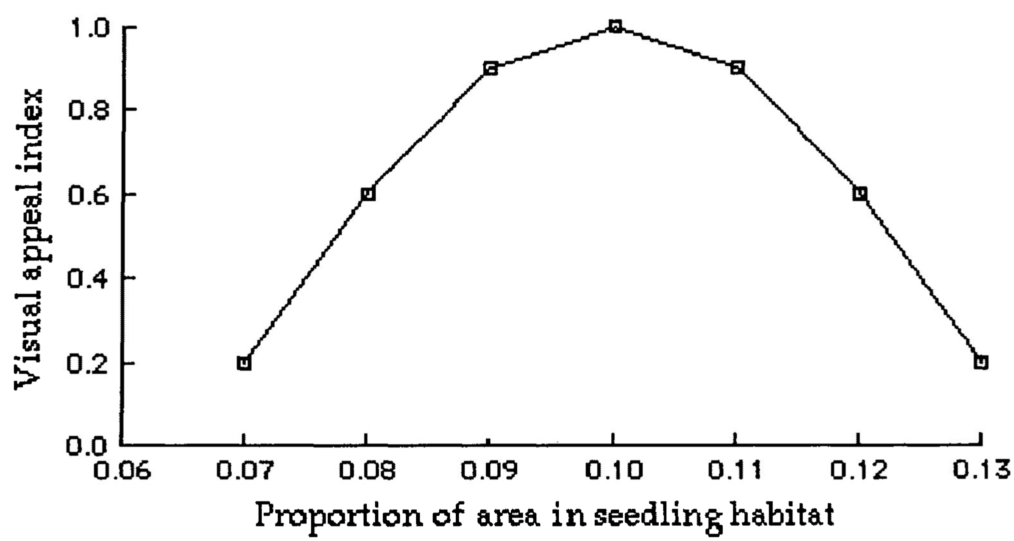

Figure 14. Visual appeal index related to the proportion of the area on seedling habitat (from Boyce 1977)

GOAL PROGRAMMING MODEL (GP)

The STELLA model can illustrate to forest managers the long term development of forest stands and values under various management policies. Based on the results from the STELLA model, goal programming (GP) may guide the managers in making more specific plans by listing and evaluating all constraints and demands by developing conceptual insights of the effect of land-use decisions by quantifying perceived goals, options, and priorities.

GP Modelling Procedures

Since the GP model formulation was based on the results of the STELLA model, its formulation for the study will be explained in the next chapter. But its procedures and approaches are discussed here.

Several steps are required to represent a multiple-use problem by quantitative relationships. They are:

(1) Identification of the physical characters of the study area, such as species, site class, etc. and divide the area into several main working groups by species and site class. Each working group is divided into age-classes.

(2) Determination of several alternative multiple-use policies subject to existing socioeconomic needs and demands.

(3) Collection of data by means of field surveys, existing inventory map, and consulting with relevant experts.

(4) Identification of goals for each benefit and examine all the resulting goals as function of the planning horizon (number of target years).

(5) Identification of the constraints associated with the land-use area, e.g. area per age-class.

(6) Determination of the land capability coefficients for the various uses of the different working groups and age-classes.

GP Modelling Approach

(1) Goal target level.

Goal target levels for each benefit and each planning period can be set by simulation results of the STELLA model. In this way, each target level would be more reasonable and more practical.

(2) Timber benefits.

The mean volume per ha of gross merchantable timber was used as the coefficient for timber in the GP model.

(3) Wildlife benefits (moose).

The dry weight of browse (kg/ha) was used in the model as the coefficient of moose potential.

The areas of coniferous species for winter cover were also computed. According to Allen *et al.* (1987), pure or mixed coniferous stands with a height greater than 10.6 m are suitable for moose cover. Thus the total area of cover was calculated based on corresponding age and site classes.

(4) Aesthetic potential.

It is assumed that the forest stands along roads and water bodies are more important in terms of aesthetic value than other stands. Because aesthetic value is considered to be related to outdoor recreation, and the greater part of the total recreation visits to forests takes place along roads, and trails, and along streams and lakes (Clawson 1975), this kind of area is called a sensitive area, or a visual enhancement area (Sloan, 1986). In this study, only those areas along roads and lakes were considered to have aesthetic value, and a sensitive area (SA) zone was created. The rotation of the stands in the SA zone was prolonged in order to reduce the impacts from harvesting operations and preserve old forest stands which have a higher aesthetic value. Therefore, area constraints were used in the model. Forest aesthetics was not listed directly as an objective function in the model.

CASE STUDY

STUDY AREA

The study area was located approximately 75 km northeast of Thunder Bay, Ontario, Canada (Figure 15a). The geographical location is from about 48° 51' to 48° 55' north latitude, and from 89° 10' to 89° 20' west longitude. It is part of management unit No. 030 of Abitibi-Price Spruce River Forest. The area is bounded on the east by Highway 527, on the north and west by Mile 35 Road , and on the south by Pace Lake Road. Total productive area is 2938 ha (Figure 15b).

The topographic feature of the area has been classified as a weakly broken plain, and the soil is characterized by shallow sandy tills over bedrock (OMNR, 1982).

Black spruce (Picea mariana (Mill..) B.S.P), jack pine (Pinus banksiana Lamb), white birch (Betula papyrifera Marsh), aspen (Populus spp L.), and balsam fir (Abies balsamea(L.) Mill) are the main tree species in the area.

As its location is not far away from the community (less than 100 km to the city of Thunder Bay) and accessibility is good, the area has potential for forest recreation, such as hunting, walking,

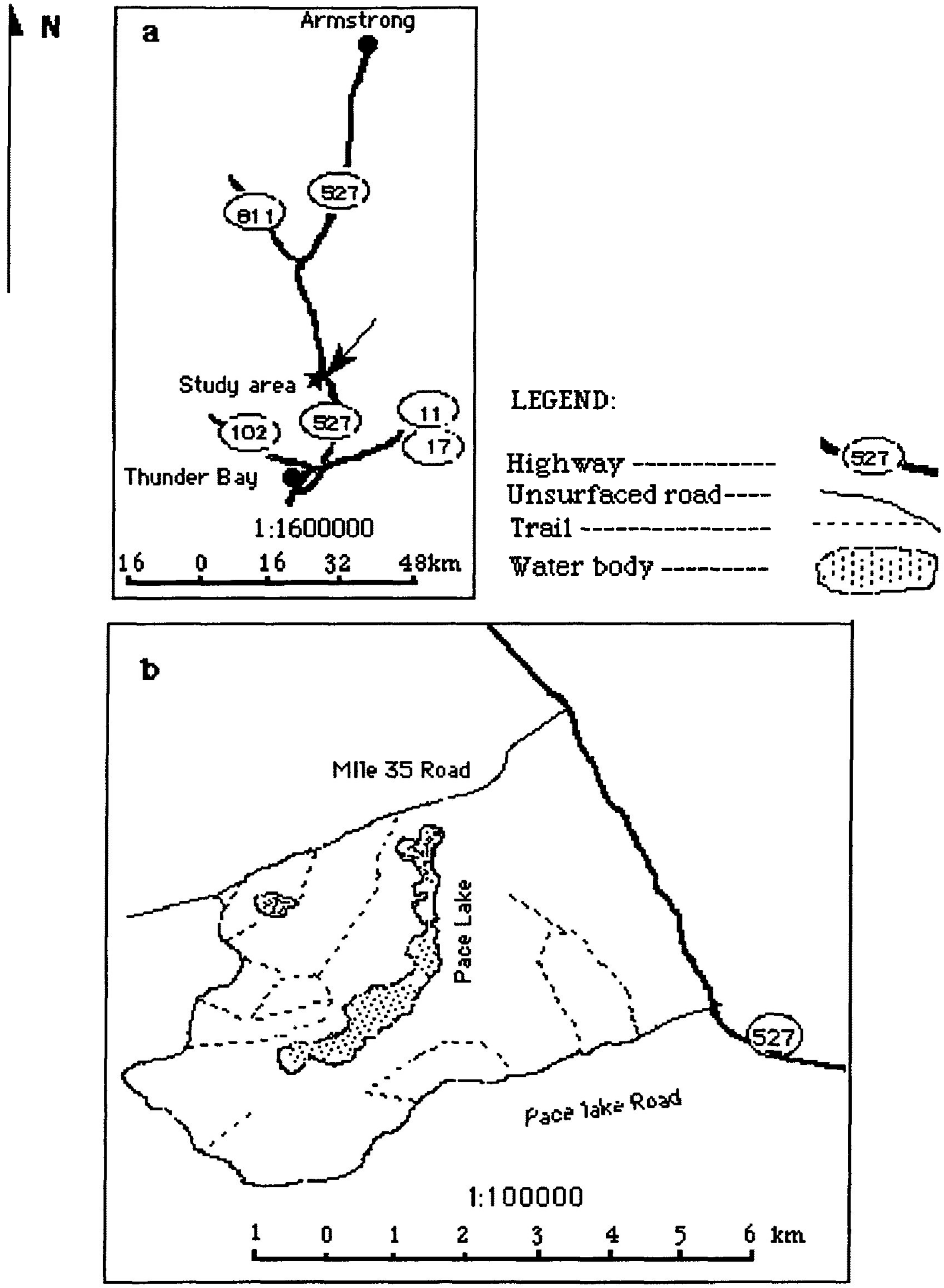

Figure 15. The geographic location (a) and the local situation of the study area (b)

blue berry picking, fishing and cross-country skiing. Since Pace Lake lies inside the study area, it is possible that in the future the land around the lake may be sold for building cottages, similar to the development around Edmondson Lake which is close to the study area. According to the OMNR (1982), the area has a moderate density of moose distribution , indicating that it is in a position to provide opportunities for hunting and wildlife viewing.

The area is currently managed under agreement #500700 between the OMNR and Abitibi-Price Inc. (OMNR, 1987). Figure 16 shows the current age-class distribution in hardwood and softwood working groups. About 37 percent of the total area has been logged in the last 10 years, leaving the distribution of age-classes in an uneven state (Figure 16).

Although timber production was considered to be the primary objective in the forest management agreement, some areas of forest lands, because of their location or nature, should be managed in consideration of multiple-use (OMNR, 1987). Since the location of the study area is within the community's reach, public concern for some non-timber benefits should be regarded as important as timber. Therefore, the area was selected as an example for integrated forest resource management.

STAND CLASSIFICATION

Based on the forest resource inventory map (OMNR 1985), the

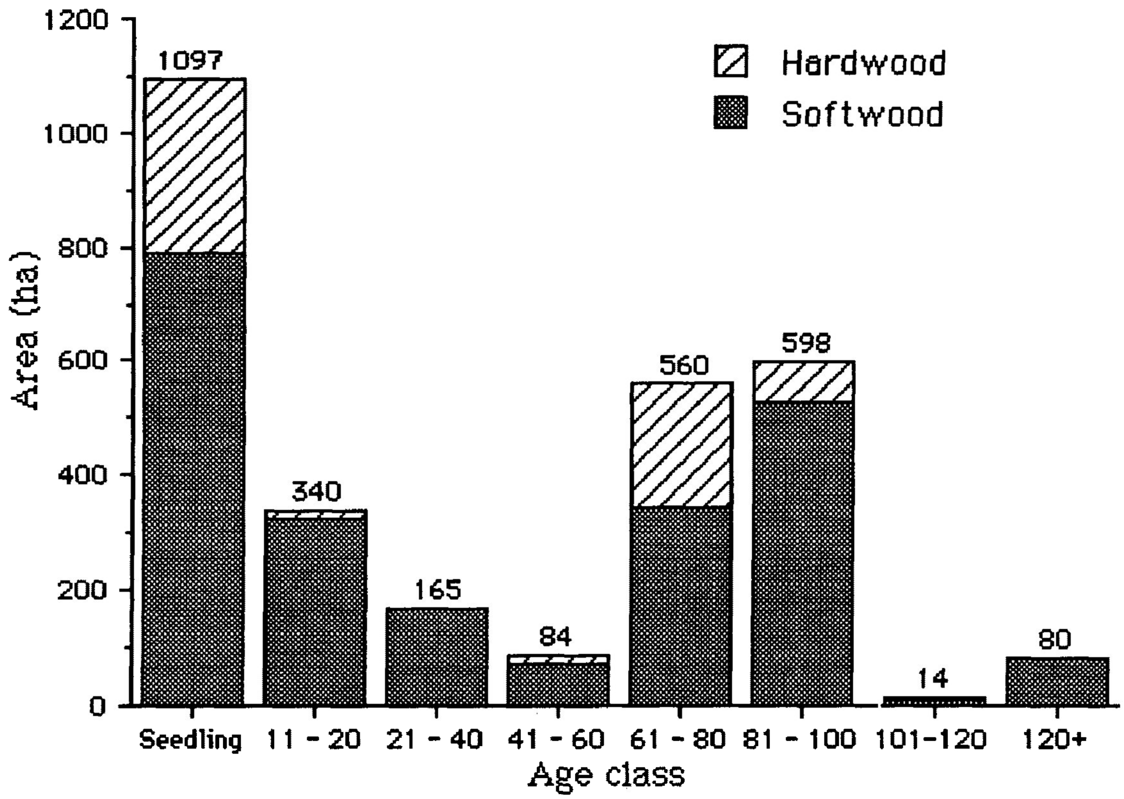

Figure 16. The age-class distribution of both softwood and hardwood working-groups of the study area

age of forest stands was updated to 1991. The total number of forest stands is 76, and the area of individual stands ranges from 3 to 265 ha. Stands were classified into working groups by species. The main working groups are black spruce and aspen, which contain 54 and 13 stands respectively. There are other working groups in the study area, such as jack pine, cedar, balsam fir, larch and white birch. Since those working groups have very few stands, the coniferous species stands (two jack pine dominated stands, two cedar dominated stands, three balsam fir dominated stands, and one larch dominated stand) were incorporated into the black spruce working group, and the deciduous species stand (one white birch dominated stand) into the aspen working group. The black spruce working group was further divided into two sub-groups: site class 1 (SC 1) and 2 (SC 2). Two stands which belong to site class 1a were put in SC 1 sub-group, and five stands which belong to site class 3 and 4 were incorporated into the SC 2 sub-group. No sub-division was made for the aspen working group, because eleven of the total 14 stands belong to site class 2, and the remaining 3 stands were treated as the same site class. Table 2 lists the area of working groups by age-classes.

THE LAND CAPABILITY COEFFICIENTS

I. Timber

In order to determine the average volume of gross

Table 2. Inventory lists by working groups

Age class	Black spruce working group		Aspen working group	Total
	SC[a] 1	SC 2	SC 2	
	ha			
seedling	458	329	310	1097
11 - 20	147	177	16	340
21 - 40	19	146	0	165
41 - 60	57	17	10	84
61 - 80	289	53	218	560
81 - 100	471	56	71	598
101 - 120	6	4	4	14
120 +	76	4	0	80
Total	1523	786	629	2938

a. SC - Site class

merchantable timber per ha, the data in the yield table (Plonski, 1974) were used according to the site class and species studied. The present average stocking level in the study area is 0.6, which was used to calculate the yield rate of gross merchantable timber volume. These values represented the timber coefficients in the GP model.

II. Winter browse availability for moose

A. Black spruce working group

In order to determine dry weight of browse per ha, a vegetation survey was conducted in August, 1991. Within two black spruce sub-working groups, a total of 17 stands, between 5 to 30 years old, were randomly selected.

The survey was carried out by sampling plots of 20 m by 1 m (1/500 ha) systematically distributed (with the first plots randomly selected) on equidistant lines. The following 11 species were recognized as browse species:

white birch	Betula papyrifera Marsh
balsam fir	Abies balsamea (L.) Mill
mountain ash	Sorbus americana Marsh
willows	Salix spp L.
mountain maple	Acer spicatum Lam.
dogwood	Cornus alternifolia L.f.
cherries	Prunus spp L.
aspen	Populus spp L.
june berries	Amelanchier spp L.

beaked hazel *Corylus cornuta* March
green alder *Alnus crispa* (Ait.) Pursh

The twig count method (Cumming 1987) was used in the vegetation inventory. In each plot, the stems of each species were recorded into three height classes (0.5 - 1.0 m, 1.01 - 2.0 m, 2.01-3.0 m). At every fifth plot, the number of browsable twigs of each stem were recorded. Therefore, the total number of twigs of each species in all three height classes on each plot can be tallied.

Dry weight of the browse per twig was estimated by using the result of Nisbet (1981). The result of the field vegetation inventory is shown in Tables 3 and 4.

From Tables 3 and 4, it can be seen that the differences in dry weight (kg/ha) among stands are not as obvious as that in the number of stems per ha. In fact, the dry weight of some stands that have fewer stems is higher than that of stands which have more stems. This situation may be explained by two facts: first, the proportion of shrubs in a higher height class in older stands tends to be larger than in younger stands, and individual stems that fall into higher height classes have more browse twigs than those that fall into lower height classes. Therefore, although an older stand has fewer stems per ha than a young stand, sometimes the former has more browse twigs than the latter; second, the dry weight of an individual twig is different among species, and the shrub species composition changes as the stand grows. The proportion of coniferous species (balsam fir) in a younger stand is smaller than in an

Table 3. Browse availability in site class 1 sub-working group

Stand age	Number of plots	Stems (stems/ha)	Dry weight (kg/ha)
5	64[1]	13600	62
10	98[2]	26100	197
15	32	21500	187
20	36	13700	133
25	22	9100	104
30	18	7400	96

1 - Total number of plots on 2 sampling points

2 - Total number of plots on 3 sampling points

Table 4. Browse availability in site class 2 sub-working group

Stand age	Number of plots	Number of Stems (stems/ha)	Dry weight (kg/ha)
5	61[3]	11400	50
10	64[4]	23500	162
15	33	19500	165
20	36	13500	131
25	28	11700	120
30	19	9300	113

3, 4 - Total number of plots on 2 sampling points older stand, and a twig of balsam fir has several times as much dry weight as a twig of deciduous species.

The per ha yield of dry weight of browse in Tables 3 and 4 was used as coefficients for black spruce working group in the GP model. Since older stands do not produce as much available browse as recently cut-over (less than 20 years) area (Schwartz and Franzmann 1989; Vallée *et al.* 1976), and stands with sparse browse densities contribute no value to available moose browse (Allen *et al.* 1987), only stands less than 40 years old were considered to produce available browse in this study. The per ha yield of browse production in stands at age 30 in Tables 3 and 4 were used as coefficients for stands between 30 and 40 years old.

B. Aspen working group

The browse per ha was not investigated for the aspen working group because there were only 8 stands in the younger age classes. According to Vallée *et al.* (1976), the trend of changes in browse production potential in hardwood stands is much different from that in softwood stands. A 70 year-old stand can produce as much browse as a 20 year-old stand; therefore, stands at all ages were considered to produce available browse in this study. In order to make projections for the poplar working group, the results of Vallée *et al.* (1976) for hardwood working groups (Table 5) were used as coefficients for predicting browse production potential of poplar working group. The average number of browse stems between 22 and 70 years were used as coefficients for the age-classes over 20

Table 5. Browse availability in hardwood working group

Stand age	Number of stems (stems/ha)	dry weight [a] (kg/ha)
5	21050	178
12	25250	213
15	19375 [b]	163
22	13500 (15350 [c])	114
22 +	14425 [d]	122

Source: Vallée *et al.* (1976)

a. Dry weight was calculated by multiplying number stems per ha and mean weight per stem

b. The average number of stems per ha in stands between 12 and 22 years old

c. The number of stems per ha at 70 years

d. The average number of stems per ha in stands between 22 and 70 years old

Table 6. The characteristics of the study area for aesthetics in the SA zone

features	total length (km)	area (ha)
highway	4.7	94
road	18.4	368
trail	10.2	204
lake edge	5.6	167
Total		833

years old. Dry weight (kg/ha) was estimated based on the mean weight of stems from Tables 3 and 4.

III. Forest aesthetics

Based on the inventory map, the length of those stands along highways, roads, trails and lakes was measured. After consulting with Dr. Akervall[2], I extended the depth of the buffer zone for highways and roads to 200 m, for trails to 100 m, and for lakes to 300 m. The area of each stand devoted to forest aesthetics was computed and subtracted from the area of that stand. The total area devoted to aesthetics was classified into working groups. Therefore, the study area was divided into two zones. One is the sensitive area (SA) zone, which includes the buffer area calculated above, the other is the timber area (TA) zone, which includes the total area away from roads, trails, and lakes. Table 6 (page 65) shows the total length of highway, road, trail and the edge of the lake, and the area for each feature. Appendix 4 shows the inventory listings of TA and SA zones.

BASIC ASSUMPTIONS

The following assumptions were considered for this study

Planning horizon	30 years
Base year	1991

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[2] Professor of the School of Outdoor Recreation, Parks and Tourism, Lakehead University.

Planning period 5 years

Management alternatives

Alternative one : (MA one) Managing the forest stands under a timber only policy. Harvesting all forest stands at a normal rotation age. In this study, the rotation age was set at 90 years for all the working groups.

Alternative two : (MA two) Managing the forest in terms of multiple-use. harvesting stands in the TA zone at 90 years. The harvesting of stands in the SA zone was delayed to 130 years to decrease disturbances of the stands, in order to increase the aesthetic value.

Alternative three : (MA three) This is also a multiple-use policy. The difference from MA two was to delay the harvesting of the stands in the SA zone to 170 years. This alternative would further increase the aesthetic value in the SA zone.

RESULTS AND DISCUSSION

Application of The STELLA Model

The STELLA model runs for the three management alternatives were completed by using the STELLA software (Richmond *et al.* 1987) installed on a Macintosh plus computer. The simulation results for each management alternative are presented in the form of a table and four graphs.

Management Alternative One

Table 7 and Figures 17 - 20 show the results of the simulation. They show the trends produced by implementing management alternative one (MA one). The distribution of age-classes or habitats and the indices for benefits reached a steady state at about 80 years, when the total area was almost equally distributed among the age classes or habitats (Table 7), the timber potential index (TPI) was close to 1 (maximum level), the aesthetics potential index was very low (about 0.32), and the moose potential index (MPI) about 0.63 (Table 7, Figure 17). Figures 18 and 19 show the trends of changes of variables to be used in estimating moose and aesthetics potential indices. Since timber was regarded as the most desired objective in this alternative, all the stands were harvested at

Table 7 The simulation results by the STELLA model for management alternative one.
(The definitions of the symbols are shown in Appendix 1)

Time	MPI	API	TPI	MTH	OGH	TOH	SE	AGE15	AGE30	AGE50	AGE70	MTR	OGR	BAL	PSE	POG	PG20	PL20
0	1.000	0.068	0.000	0.0	0.0	0.0	1097	340	165	84	560	692	0.0	0.743	0.373	0.0	0.511	0.489
1	1.000	0.068	0.000	0.0	0.0	0.0	987	416	191	88	536	720	0.0	0.747	0.336	0.0	0.522	0.478
2	1.000	0.068	0.059	1.8	0.0	1.8	889	473	223	93	514	747	0.0	0.752	0.302	0.0	0.537	0.463
3	1.000	0.068	0.136	4.1	0.0	4.1	801	514	259	100	493	771	0.0	0.755	0.273	0.0	0.552	0.448
4	1.000	0.068	0.289	8.6	0.0	8.6	725	543	297	108	473	791	0.0	0.756	0.247	0.0	0.568	0.432
5	1.000	0.068	0.419	12.5	0.0	12.5	661	561	337	117	455	806	0.0	0.752	0.225	0.0	0.584	0.416
6	1.000	0.068	0.527	15.7	0.0	15.7	608	571	376	128	438	817	0.0	0.745	0.207	0.0	0.599	0.401
7	0.984	0.067	0.618	18.4	0.0	18.4	563	575	414	141	422	823	0.0	0.736	0.192	0.0	0.613	0.387
8	0.968	0.067	0.695	20.7	0.0	20.7	525	574	451	154	408	826	0.0	0.724	0.179	0.0	0.626	0.374
9	0.952	0.080	0.759	22.6	0.0	22.6	493	569	486	169	396	825	0.0	0.711	1.168	0.0	0.639	0.361
10	0.936	0.134	0.814	24.2	0.0	24.2	466	561	519	185	384	823	0.0	0.697	0.159	0.0	0.650	0.350
15	0.873	0.260	0.979	29.2	0.0	29.2	385	505	645	274	347	781	0.0	0.624	0.131	0.0	0.697	0.303
20	0.827	0.275	1.000	31.3	0.0	31.3	351	449	717	365	340	716	0.0	0.561	0.120	0.0	0.728	0.272
25	0.797	0.271	1.000	31.9	0.0	31.9	337	406	749	448	354	644	0.0	0.514	0.115	0.0	0.747	0.253
30	0.769	0.274	1.000	26.3	0.0	26.3	318	375	757	518	382	588	0.0	0.493	0.108	0.0	0.764	0.236
40	0.704	0.267	0.972	22.9	0.0	22.9	266	319	732	610	457	554	0.0	0.524	0.091	0.0	0.801	0.199
50	0.633	0.272	0.852	24.1	0.0	24.1	245	275	675	649	527	567	0.0	0.593	0.083	0.0	0.823	0.177
60	0.606	0.289	0.879	26.5	0.0	26.5	251	256	616	647	577	590	0.0	0.659	0.085	0.0	0.827	0.173
70	0.610	0.307	0.935	28.5	0.0	28.5	268	258	575	626	601	610	0.0	0.702	0.091	0.0	0.821	0.179
80	0.628	0.319	0.977	29.7	0.0	29.7	284	270	556	601	606	622	0.0	0.718	0.097	0.0	0.811	0.189
90	0.646	0.324	0.988	30.0	0.0	30.0	294	283	555	582	600	625	0.0	0.715	0.100	0.0	0.804	0.196
100	0.659	0.323	0.988	29.8	0.0	29.8	297	291	563	573	591	623	0.0	0.704	0.101	0.0	0.800	0.200
110	0.665	0.320	0.988	29.5	0.0	29.5	297	295	573	571	583	620	0.0	0.693	0.101	0.0	0.798	0.202
120	0.665	0.317	0.988	29.2	0.0	29.2	294	295	580	573	578	617	0.0	0.686	0.100	0.0	0.799	0.201
130	0.663	0.315	0.987	29.0	0.0	29.0	292	294	584	577	577	615	0.0	0.682	0.099	0.0	0.801	0.199
140	0.660	0.314	0.986	28.9	0.0	28.9	290	292	585	580	577	614	0.0	0.682	0.099	0.0	0.802	0.198
150	0.667	0.314	0.985	28.9	0.0	28.9	289	290	584	582	579	614	0.0	0.684	0.099	0.0	0.803	0.197
160	0.667	0.315	0.984	29.0	0.0	28.9	289	290	582	582	580	615	0.0	0.685	0.099	0.0	0.803	0.197

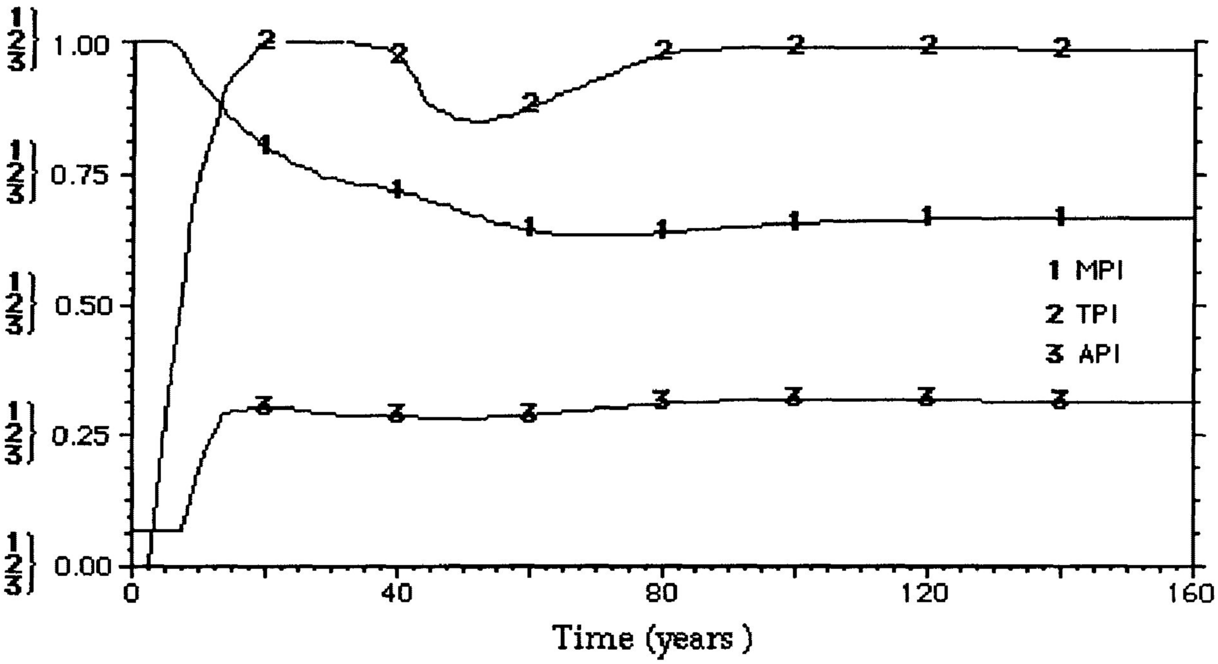

Figure 17. The trend of changes of benefit potential indices under management alternative one

1. MPI - Moose potential index; 2. TPI - Timber potential index; 3. API - Aesthetics potential index

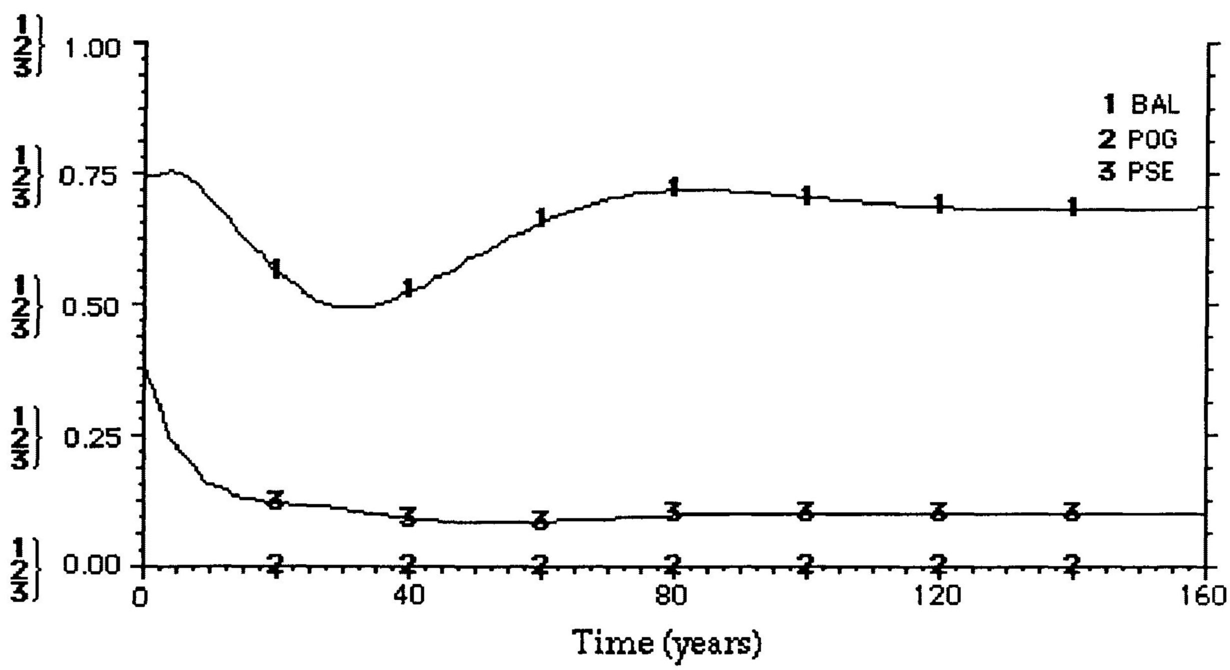

Figure 18. The changes of variables for estimating forest aesthetics under management alternative one

1. BAL - Balance between two height classes; 2. POG - Proportion of the area in old-growth reserves; 3. PSE - proportion of the area in seedling habitat.

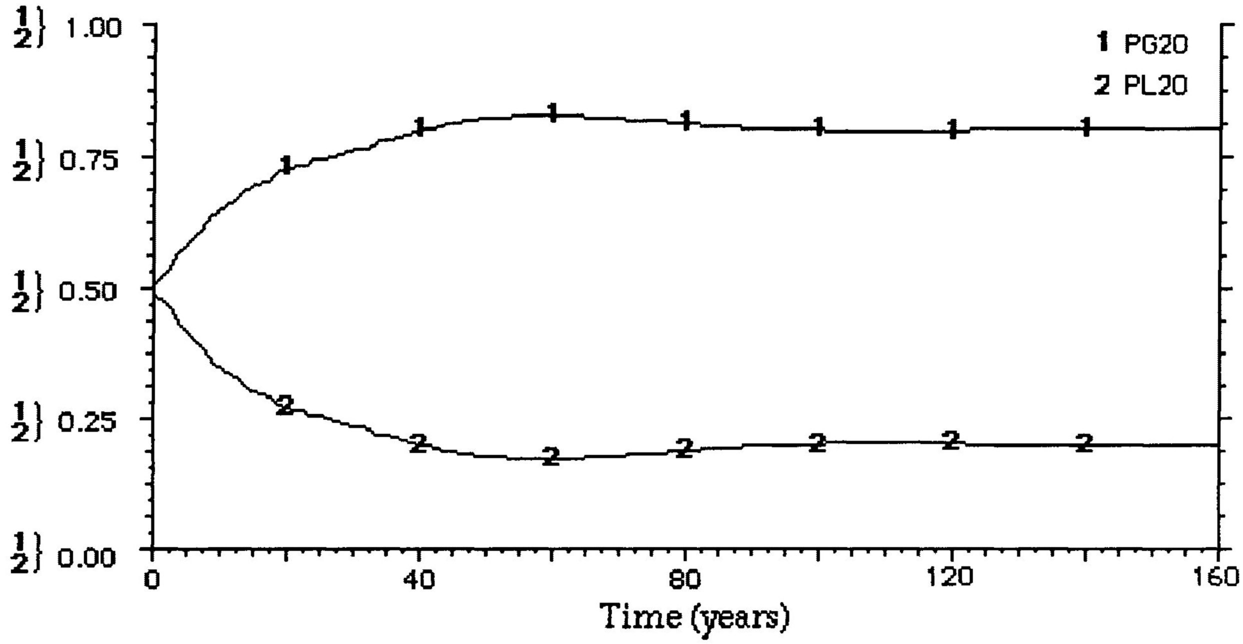

Figure 19. The changes of variables for estimating moose potential index under management alternative one
1. PG20 - Proportion of the area in deciduous or mixed forest stands (≥ 20 years old); 2. PL20 - Proportion of area in shrub or forest stands < 20 years old.

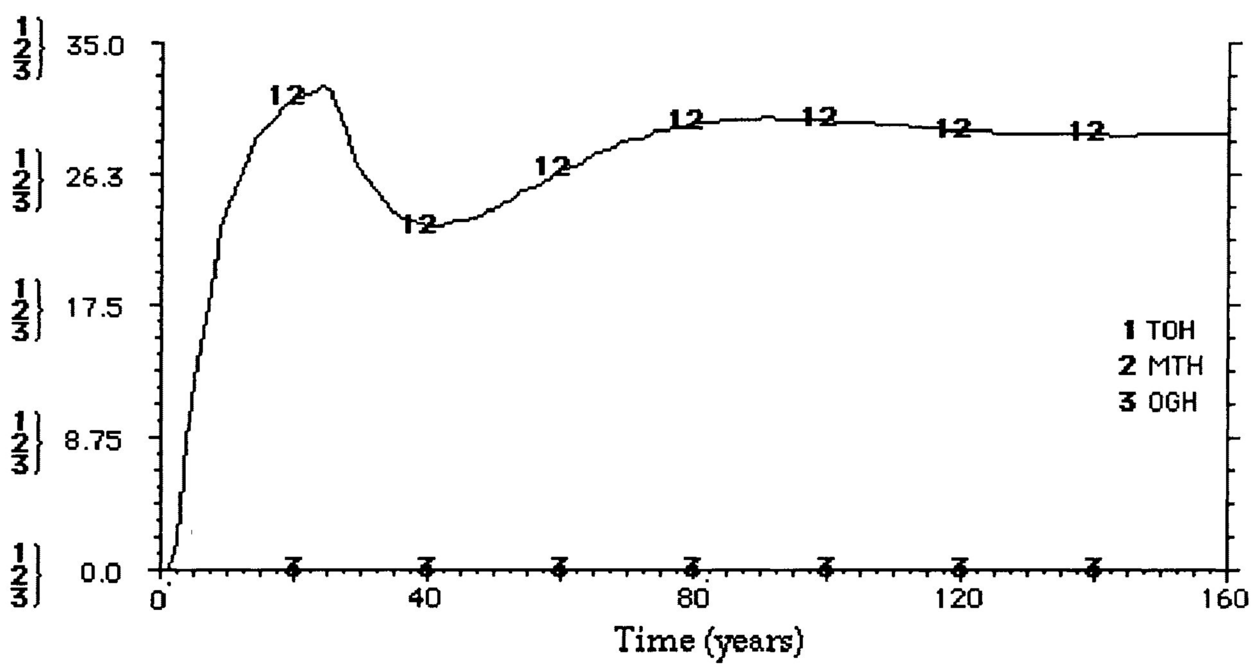

Figure 20. The annual harvest area of both mature (MTH) and old-growth (OGH) under management alternative one
1. TOH - Total harvest; 2. MTH - Mature timber harvest; 3. OGH - Old-growth harvest.

maturity, and the proportion of old-growth (POG) was zero, which brought about a lower API. The trends of changes in annual harvest area (ha) are shown in Table 7 and Figure 20. Through the feedback function, the model adjusted the distribution of age-classes or habitats by harvesting. Since the proportion of seedling habitat (PSE) in total area was very large in the initial inventory, the area of mature timber harvest (MTH) was zero at the beginning, and increased until it became steady at about 80 years. The area of old-growth harvest (OGH) was zero since there were no old-growth reserves (OGR) in this management alternative. Therefore, the total harvest area (TOH) equaled the mature timber harvest area (Figure 20).

Management Alternative Two

Table 8 and Figures 21-24 show the simulation results of management alternative two (MA two). Compared with the results from timber only policy (MA one), TPI was reduced to 0.87 of the maximum, API increased to about 0.52, and MPI decreased to 0.60 (Table 8 and Figure 21). Figures 22 and 23 show the patterns of changes of variables which were used to estimate API and MPI. The increase of API by this policy could be explained by the increase of the proportion of old-growth (POG). The changes of two variables, PL20 and PG20, related to moose potential, had similar trends as the results from MA one, only a small decrease in proportion of the area for food (PL20) to account for the decrease in MPI. The harvest

Table 8 The simulation results by the STELLA model for management alternative two (The definitions of the symbols are shown in Appendix 1)

Time	MPI	API	TPI	MTH	OGH	TOH	SE	AGE15	AGE30	AGE50	AGE70	MTR	OGR	BAL	PSE	POG	PG20	PL20
0	1.000	0.081	0.000	0.0	0.00	0.00	1097	340	165	84	560	598	94	0.743	0.3730	0.0000	0.511	0.489
1	1.000	0.082	0.000	0.0	0.00	0.00	987	416	191	88	536	619	101	0.743	0.3360	0.0023	0.522	0.478
2	1.000	0.083	0.000	0.0	0.00	0.00	889	473	223	93	514	639	108	0.744	0.3020	0.0045	0.537	0.463
3	1.000	0.084	0.046	1.3	0.00	1.30	800	514	259	100	493	658	115	0.745	0.2720	0.0068	0.553	0.447
4	1.000	0.085	0.107	3.1	0.00	3.10	721	543	297	108	473	674	122	0.745	0.2450	0.0091	0.570	0.430
5	1.000	0.086	0.216	6.3	0.00	6.30	652	561	337	117	455	688	129	0.743	0.2220	0.0113	0.587	0.413
6	0.995	0.087	0.309	9.1	0.00	9.10	593	570	376	128	438	697	136	0.739	0.2020	0.0136	0.605	0.395
7	0.975	0.088	0.401	11.4	0.35	11.75	543	572	414	141	422	703	143	0.733	0.1840	0.0159	0.621	0.379
8	0.955	0.088	0.480	13.4	0.69	14.09	500	569	451	154	408	706	149	0.725	0.1700	0.0182	0.637	0.363
9	0.936	0.186	0.548	15.0	1.01	16.01	464	562	485	169	396	706	156	0.715	0.1570	0.0206	0.652	0.348
10	0.918	0.270	0.607	16.4	1.32	17.72	434	553	517	185	384	703	162	0.705	0.1460	0.0229	0.666	0.334
15	0.840	0.422	0.801	20.9	2.61	23.51	341	484	638	273	347	667	188	0.648	0.1130	0.0344	0.724	0.276
20	0.784	0.436	0.891	22.6	3.60	26.20	303	418	699	362	339	610	207	0.598	0.0974	0.0457	0.763	0.237
25	0.745	0.421	0.814	19.9	4.26	24.16	284	367	720	441	352	553	220	0.561	0.0918	0.0551	0.787	0.213
30	0.706	0.409	0.739	18.5	4.56	23.06	262	329	716	504	378	522	226	0.539	0.0898	0.0622	0.802	0.198
40	0.617	0.383	0.711	16.5	4.71	21.21	230	273	669	581	446	509	229	0.552	0.0839	0.0697	0.821	0.179
50	0.566	0.391	0.761	17.8	4.85	22.65	223	241	606	604	506	526	232	0.609	0.0796	0.0728	0.835	0.165
60	0.551	0.436	0.827	19.5	5.13	24.63	232	232	551	593	544	548	238	0.665	0.0808	0.0752	0.837	0.163
70	0.558	0.486	0.835	20.7	5.47	26.17	247	237	518	569	559	564	244	0.701	0.0848	0.0776	0.833	0.167
80	0.575	0.506	0.852	21.3	5.78	27.08	260	248	505	545	558	571	251	0.713	0.0887	0.0797	0.826	0.174
90	0.591	0.514	0.862	21.3	6.00	27.30	268	259	506	529	549	572	255	0.710	0.0915	0.0812	0.820	0.180
100	0.602	0.513	0.866	21.1	6.12	27.22	271	266	514	521	539	569	257	0.700	0.0927	0.0820	0.816	0.184
110	0.607	0.529	0.868	20.8	6.16	26.96	271	270	523	520	532	565	258	0.689	0.0928	0.0824	0.815	0.185
120	0.607	0.528	0.869	20.5	6.15	26.65	269	270	530	523	527	561	258	0.681	0.0824	0.0824	0.815	0.185
130	0.606	0.527	0.868	20.4	6.12	26.52	267	269	533	526	526	559	257	0.677	0.0917	0.0823	0.816	0.184
140	0.603	0.525	0.867	20.3	6.08	26.38	265	267	534	529	527	559	257	0.676	0.0912	0.0821	0.817	0.183
150	0.601	0.524	0.866	20.3	6.06	26.36	264	266	533	531	528	559	256	0.677	0.0999	0.0820	0.818	0.182
160	0.600	0.523	0.865	20.4	6.05	26.45	264	265	532	532	530	559	256	0.679	0.0908	0.0819	0.818	0.182

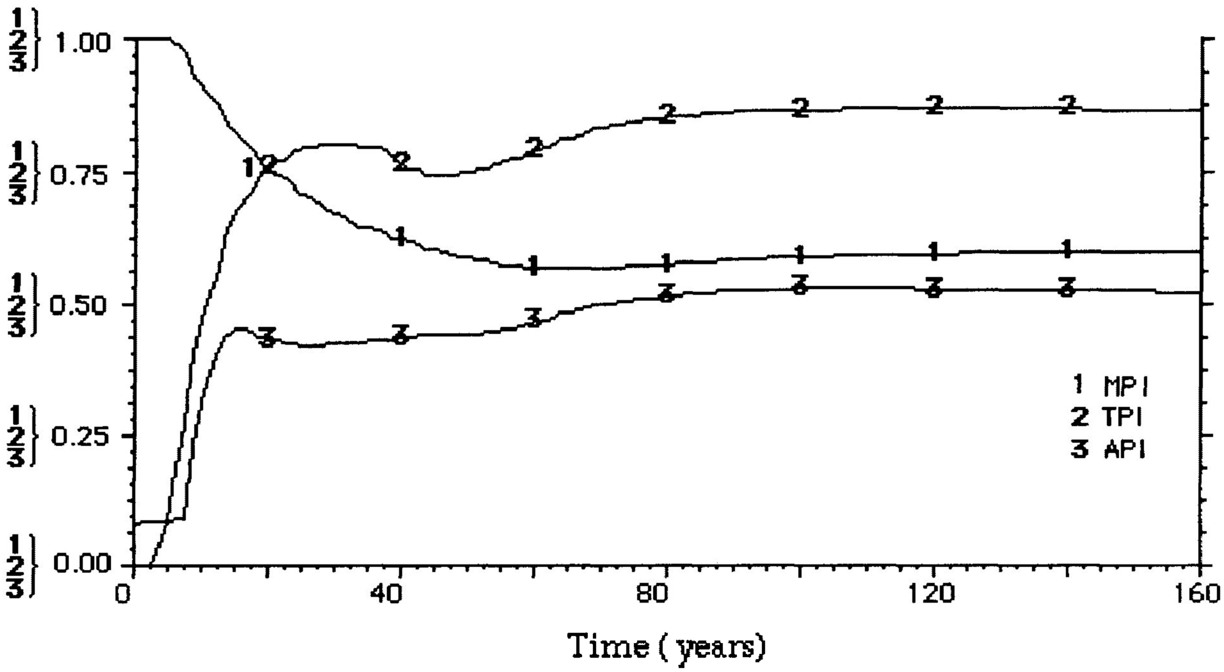

Figure 21. The trend of changes of benefit potential indices under management alternative two

1. MPI - Moose potential index; 2. TPI - Timber potential index; 3. API - Aesthetics potential index

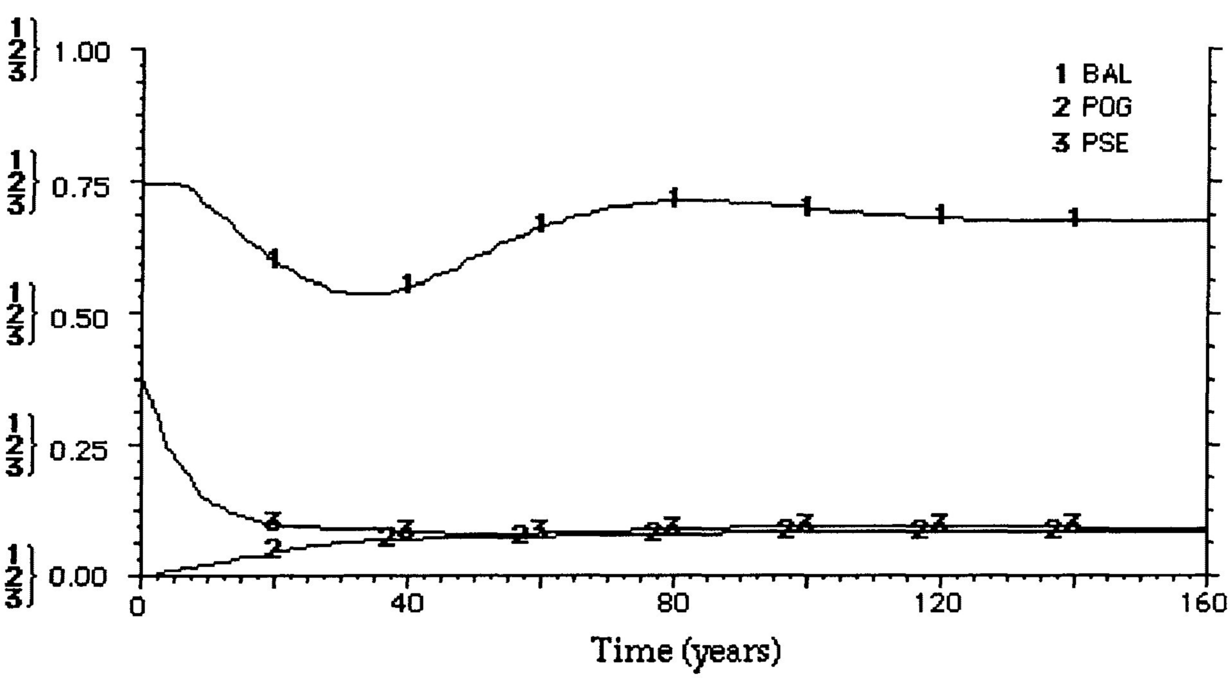

Figure 22. The changes of variables for estimating forest aesthetics under management alternative two

1. BAL - Balance between two height classes; 2. POG - Proportion of the area in old-growth reserves; 3. PSE - proportion of the area in seedling habitat.

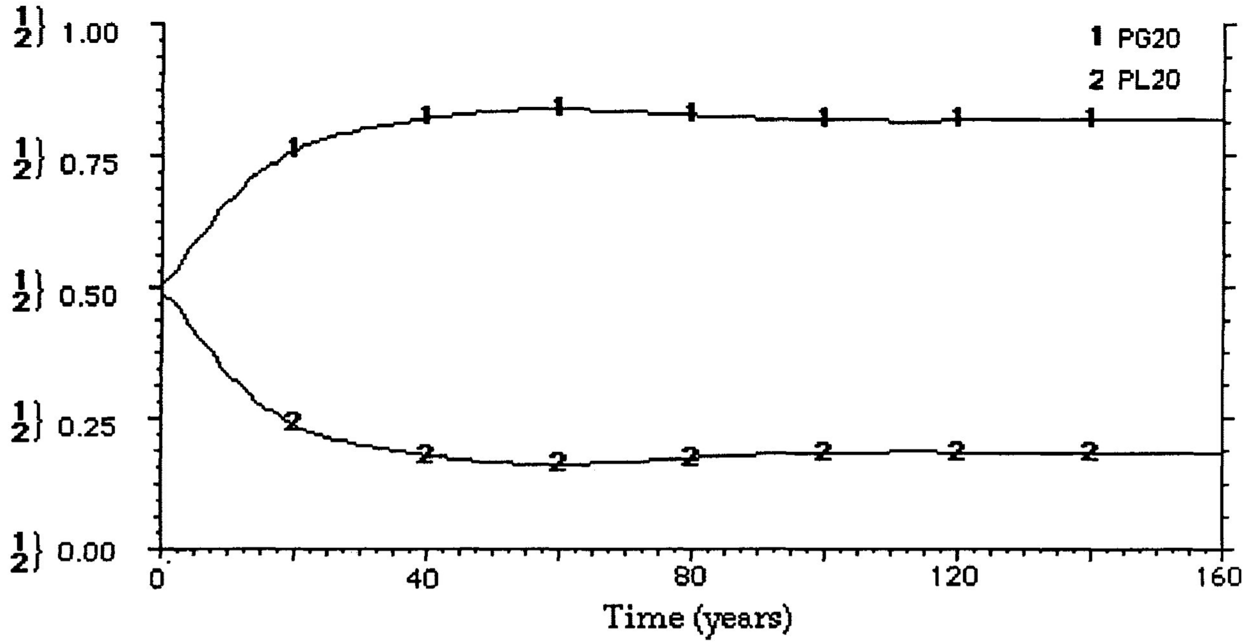

Figure 23. The changes of variables for estimating moose potential index under management alternative two

1. PG20 - Proportion of the area in deciduous or mixed forest stands (≥ 20 years old); 2. PL20 - Proportion of area in shrub or forest stands < 20 years old.

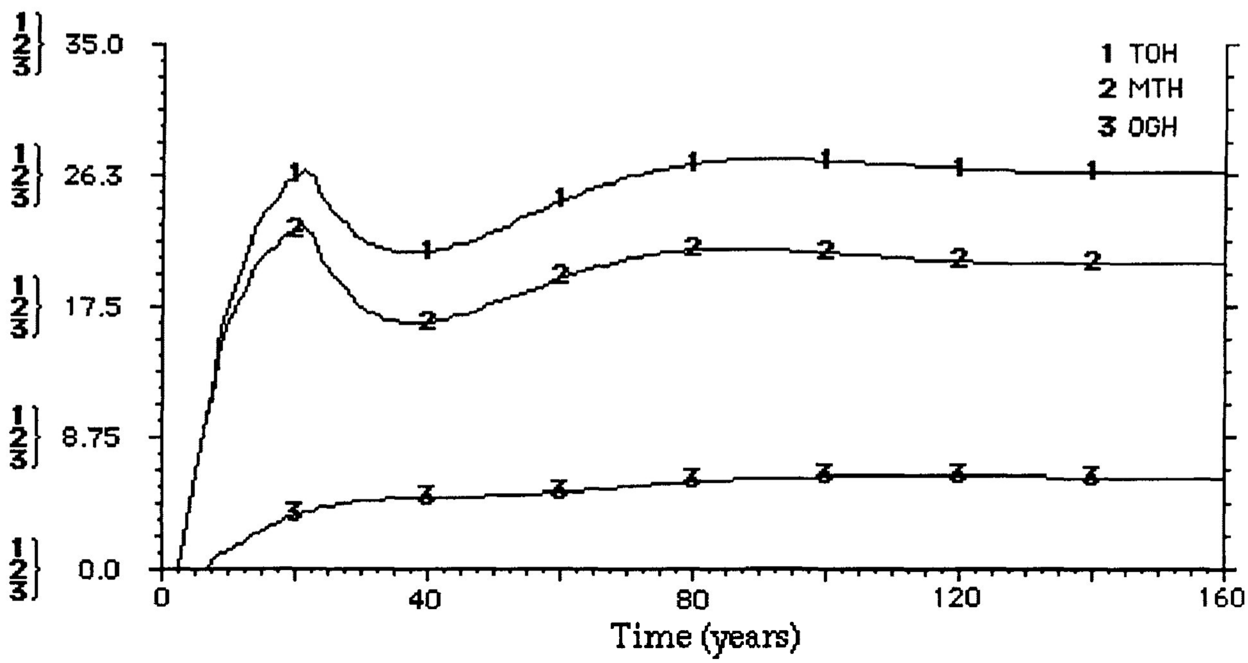

Figure 24. The annual harvest area of both mature and old-growth under management alternative two

1. TOH - Total harvest; 2. MTH - Mature timber harvest; 3. OGH - Old-growth harvest.

of old-growth (OGH) was suspended until the seventh year, and the total harvest area (TOH) was less than that by MA one (Table 8 and Figure 24).

Management Alternative Three

Table 9 and Figures 25-28 are the results of simulation for management alternative three (MA three). Since this alternative is more conservative than MA two, TPI was further lowered to about 0.80, and the value of API was almost the same as MPI (Table 9 and Figure 25). It indicated that this alternative gave more emphasis to forest aesthetics. As a result, POG became larger, and PSE got smaller compared with the other alternatives (Figure 26). The moose related variables, PL20 and PG20, only had small differences in the pattern of change from the results of the other options (Figure 27). According to Figure 28, no harvest of old-growth (OGH) was done until after 25 years, and the amount of MTH is about the same as that of MA two (Figure 28).

The simulation results show the forest dynamics under various management alternatives. Although there are no constraints on calculating any benefits in the model, the trade-off relationship among benefits could be observed from the results, such as the case between timber production and aesthetics. It is impossible to maximize both of these values at the same time. The increase of one has to be at the cost of the other. On the other hand, moose potential

Table 9. The simulation results by the STELLA model for management alternative three. (The definitions of the symbols are shown in Appendix 1)

Time	MPI	API	TPI	MTH	OGH	TOH	SE	AGE15	AGE30	AGE50	AGE70	MTR	OGR	BAL	PSE	POG	PG20	PL20
0	1.000	0.081	0.000	0.0	0.00	0.00	1097	340	165	84	560	598	94	0.743	0.3700	0.000	0.511	0.489
1	1.000	0.082	0.000	0.0	0.00	0.00	987	416	191	88	536	621	99	0.744	0.3360	0.002	0.522	0.478
2	1.000	0.083	0.000	0.0	0.00	0.00	889	473	223	93	514	642	105	0.745	0.3020	0.004	0.537	0.463
3	1.000	0.083	0.022	0.7	0.00	0.70	800	514	259	100	493	663	110	0.747	0.2720	0.005	0.553	0.447
4	1.000	0.084	0.065	1.9	0.00	1.90	720	543	297	108	473	681	115	0.749	0.2450	0.007	0.570	0.430
5	1.000	0.086	0.161	4.7	0.00	4.70	650	561	337	117	455	697	121	0.749	0.2210	0.009	0.588	0.412
6	0.993	0.086	0.262	7.7	0.00	7.70	590	570	376	128	438	710	126	0.748	0.2010	0.011	0.606	0.394
7	0.973	0.087	0.348	10.2	0.00	10.20	539	572	414	141	422	719	132	0.743	0.1830	0.013	0.622	0.378
8	0.952	0.100	0.422	12.3	0.00	12.30	495	568	451	154	408	724	137	0.737	0.1680	0.014	0.638	0.362
9	0.932	0.202	0.484	14.1	0.00	14.10	458	561	485	169	396	727	143	0.729	0.1550	0.016	0.654	0.346
10	0.914	0.284	0.537	15.7	0.00	15.70	426	551	517	185	384	727	148	0.720	0.1450	0.018	0.668	0.332
15	0.830	0.432	0.706	20.7	0.00	20.70	326	479	636	273	347	701	176	0.670	0.1110	0.027	0.727	0.273
20	0.767	0.431	0.777	22.9	0.00	22.90	282	407	695	361	339	651	203	0.625	0.0956	0.036	0.766	0.234
25	0.723	0.424	0.800	23.2	0.53	23.73	262	352	711	439	352	594	229	0.594	0.0889	0.045	0.792	0.208
30	0.679	0.426	0.756	21.6	1.09	22.69	252	313	701	500	378	544	251	0.577	0.0857	0.054	0.808	0.192
40	0.598	0.404	0.670	18.5	1.85	20.35	224	263	650	571	443	506	281	0.580	0.0815	0.071	0.827	0.173
50	0.545	0.410	0.704	19.0	2.38	21.38	213	233	587	590	500	513	302	0.619	0.0782	0.084	0.838	0.162
60	0.528	0.457	0.765	20.4	2.85	23.25	220	222	533	578	534	530	321	0.671	0.0774	0.094	0.843	0.157
70	0.533	0.517	0.813	21.5	3.28	24.78	234	226	498	552	547	543	338	0.708	0.0802	0.102	0.841	0.159
80	0.547	0.561	0.838	22.0	3.65	25.65	247	236	483	527	544	549	353	0.724	0.0838	0.108	0.835	0.165
90	0.562	0.572	0.843	22.0	3.96	25.96	254	246	483	509	533	549	365	0.722	0.0864	0.114	0.830	0.170
100	0.571	0.574	0.837	21.6	4.18	25.78	257	253	489	499	521	545	374	0.711	0.0878	0.118	0.826	0.174
110	0.576	0.571	0.827	21.2	4.33	25.53	257	256	497	497	512	540	380	0.699	0.0881	0.121	0.825	0.175
120	0.577	0.567	0.817	20.9	4.43	25.33	255	256	503	498	506	535	384	0.689	0.0877	0.123	0.825	0.175
130	0.575	0.565	0.811	20.7	4.50	25.20	253	255	506	501	503	533	386	0.683	0.0872	0.124	0.825	0.175
140	0.573	0.564	0.807	20.6	4.54	25.14	252	253	507	503	503	531	388	0.681	0.0867	0.125	0.826	0.174
150	0.571	0.564	0.807	20.5	4.57	25.07	251	252	506	505	503	531	389	0.681	0.0863	0.126	0.827	0.173
160	0.570	0.564	0.807	20.5	4.59	25.09	251	252	505	505	504	531	390	0.681	0.0863	0.126	0.827	0.173

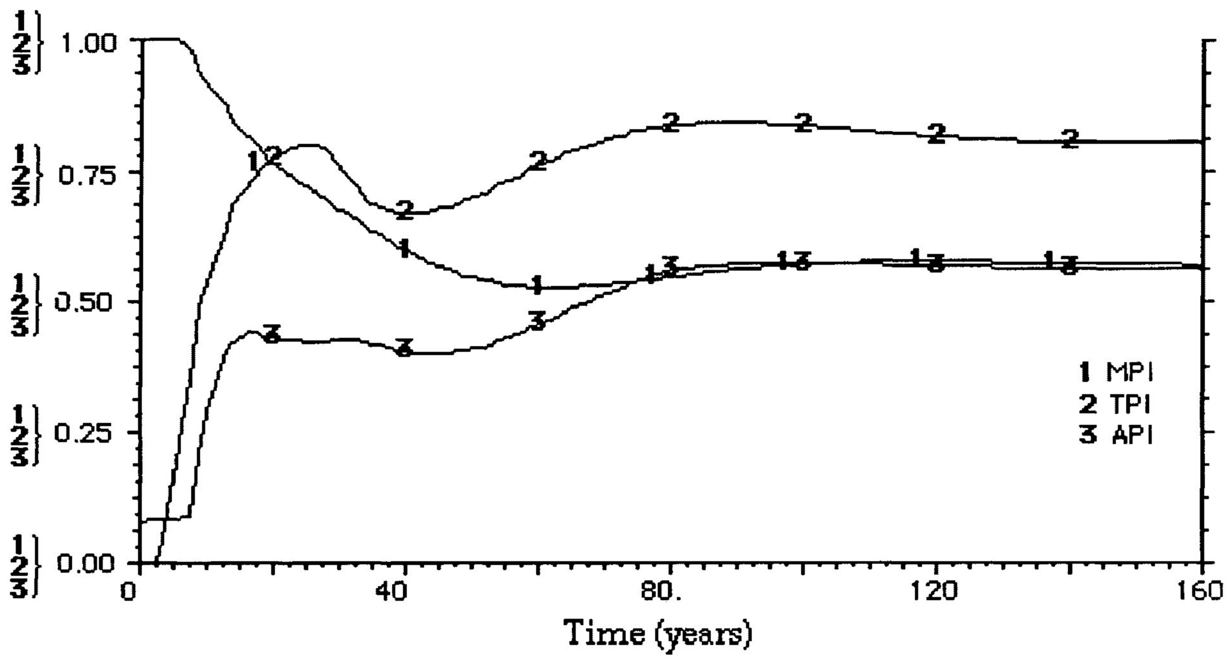

Figure 25. The trend of changes of benefit potentials under management alternative three
1. MPI - Moose potential index; 2. TPI - Timber potential index; 3. API - Aesthetics potential index

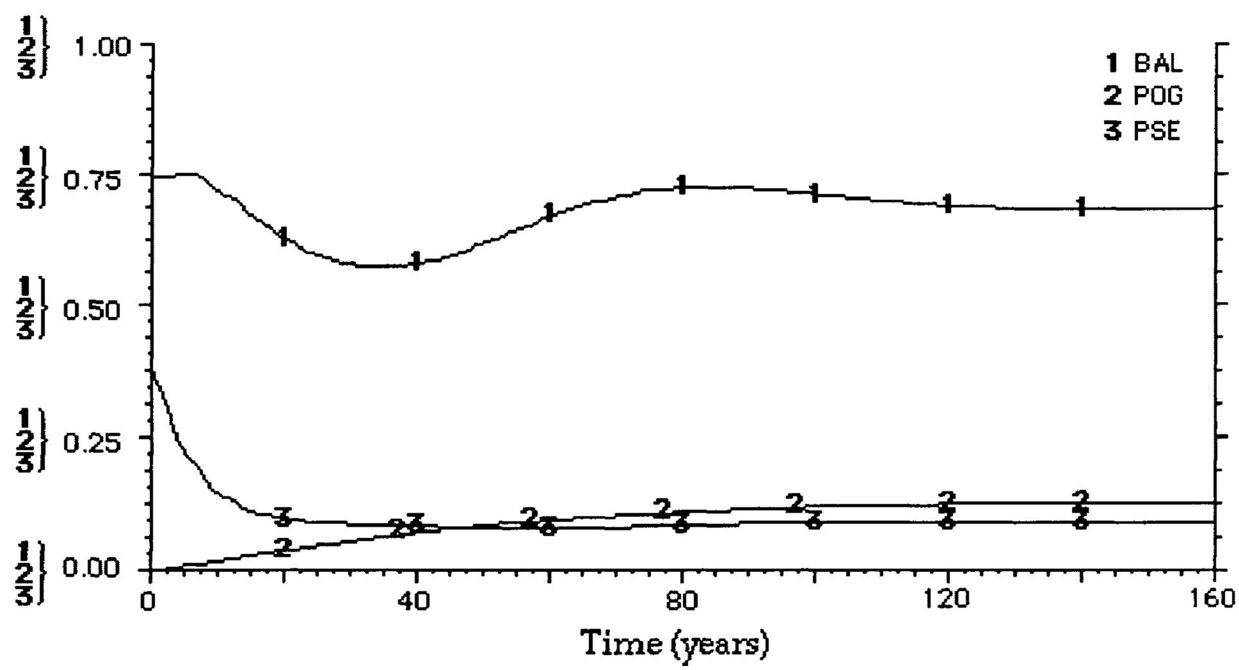

Figure 26. The changes of variables for estimating forest aesthetics under management alternative three
1. BAL - Balance between two height classes; 2. POG - Proportion of the area in old-growth reserves; 3. PSE - proportion of the area in seedling habitat.

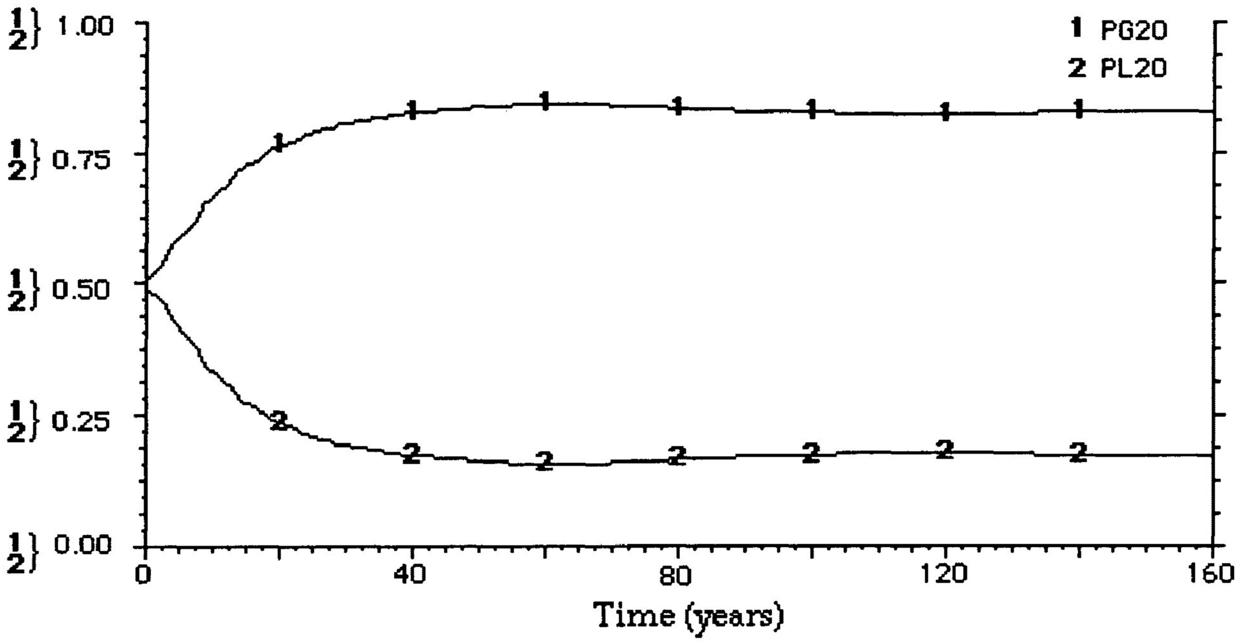

Figure 27. The changes of variables for estimating moose po tential index under management alternative three

1. PG20 - Proportion of the area in deciduous or mixed forest stands (≥ 20 years old); 2. PL20 - Proportion of area in shrub or forest stands < 20 years old.

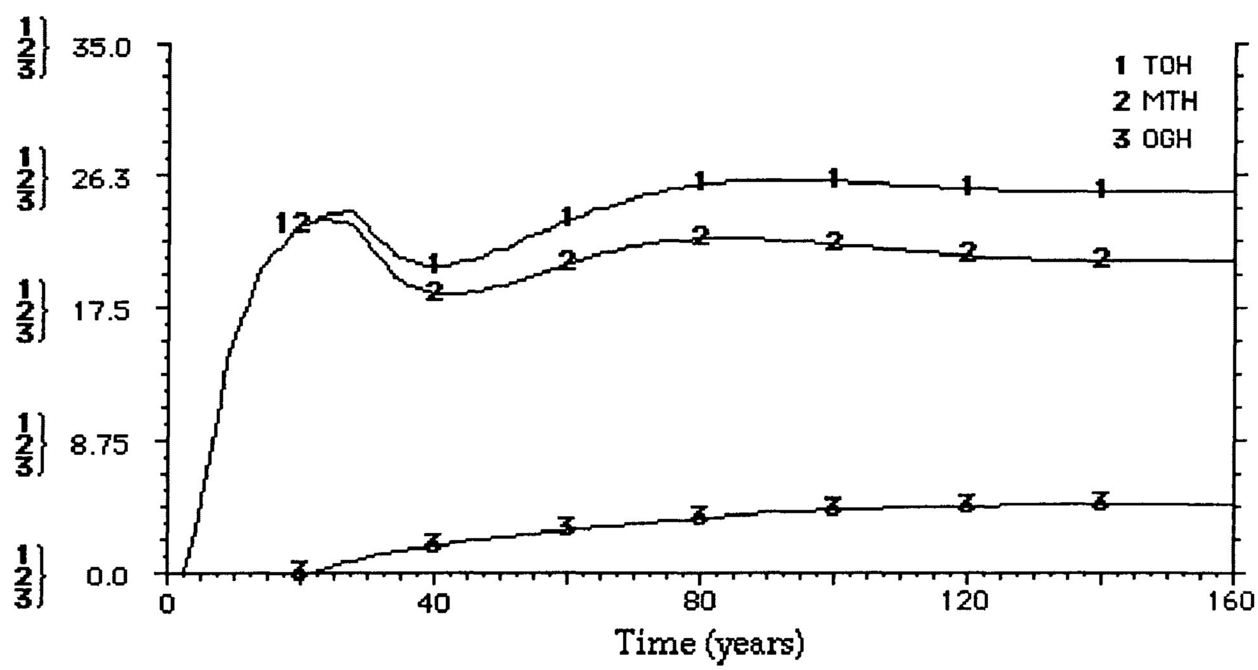

Figure 28. The annual harvest area of both mature and old-growth under management alternative three

1. TOH - Total harvest; 2. MTH - Mature timber harvest; 3. OGH - Old-growth harvest.

benefit has no such distinct trade-off relationship with timber production or with aesthetics, but the simulation results show that timber harvesting tends to increase moose potential value. This is understandable because recent cut-over areas can provide moose with browse of high quantity and quality (Telfer 1974; Allen *et al.* 1987). From the STELLA model the forest managers can get some constructive ideas about how to manage forests by comparing the results of various management alternatives. However the model treated all the forest stands as one working group, and one site class and it is unable to give a specific solution. The GP model was used to complete such a task.

Goal Programming Application

Determining Allowable Cut Area

The allowable cut area at each five year period for each management alternative was computed based on the simulation results from the STELLA model. Tables 7, 8 and 9 show the annual mature timber harvest (MTH) and old-growth harvest area (OGH) under different management alternatives. Since the planning period is a 5 year interval, the values of MTH and OGH in Tables 7, 8, and 9 had to be aggregated every five years. The results are shown in Table 10. In order to decrease deviations in cut area among periods, the mean cut area was used as the allowable cut area constraint for each period.

Table 10. The harvest area at each five-year period for different management alternatives

Period	MA[a] one	MA two		MA three	
	MTH[b]	MTH	OGH[c]	MTH	OGH
	harvest area (ha)				
5	27	11	0	7	0
10	102	65	3	60	0
15	138	97	11	95	0
20	153	110	16	111	0
25	159	117	20	116	2
30	161	111	22	113	4
Total	740	511	72	502	6
Mean	123	85	14[d]	84	3[e]

a. MA - Management alternative;

b. MTH - Mature timber harvest;

c. OGH - Old-growth harvest;

d. Mean harvest area in 5 periods (not including the first period);

e. Mean harvest area between periods 5 and 6 (not including the first four periods).

Establishing The Goal Target Levels

As mentioned above, if the forest were managed under MA two or three, the forest stands would be divided into the timber area (TA) zone and the sensitive area (SA) zone. The old-growth harvest (OGH) was referred to as harvest operation taking place in the SA zone, and the mature timber harvest (MTH) in the TA zone. The target levels for merchantable timber were established based on the mean harvest area per period for the three alternatives (Table 10). Since the STELLA model treated the forest as one working group, the allowable cut area had to be divided among working groups and site classes. The method to calculate the area harvested from different working groups and in different site classes was: First, the proportion of the area in each working group and site-class sub-group was computed based on the data in Appendix 4. For example, Appendix 4 shows the total area is 2938 ha, 1545 ha and 764 ha for site class 1 and site class 2, respectively, in the Sb working group, and 629 ha in the Po working group. The proportion for site classes 1 and 2 in the Sb working group was 53 and 26 percent respectively, and for the Po working group, 21 percent. It can be calculated that the mean area cut at each five year period under MA one is 65 ha, 32 ha, and 26 ha respectively for site class 1 and 2 in Sb working group and Po working group based on the data (123 ha) in Table 10. In the same way, the mean allowable cut area per period under MA 2 and MA 3 can be divided among the working groups and site classes. The results are shown in Table 11. Second, the gross merchantable timber data on black spruce (site classes 1 and 2) and aspen (0.6 stocking) in the yield table (Plonski 1974) were used to determine the harvest volume levels. The results are shown in Table 12.

The annual browse production goal at each five year period for each alternative was set based on the distribution of age-classes (0-40 years) for every fifth year from the simulation results of STELLA model (Table 7, 8, and 9). The data in Tables 3, 4 and 5 were used to calculate browse production. Taking the data on the fifth year in Table 7 as an example, it shows that the area for seedling habitat (0-10 years) is 661 ha, for age-class 11-20, 561 ha, for age-class 21-40, 337 ha, and for age-classes over 40 years, 1379 ha. Based on the proportions calculated previously, the area of site classes 1, 2 (Sb working group) and Po working group in each age class was computed, and multiplied by the corresponding browse yield per ha in Tables 3, 4, and 5. Therefore, the browse goal level at the fifth year under MA one was calculated to be 244.5 tons (Table 13). In the same way, all the browse goal levels at every fifth year under each management alternative were obtained (Table 13).

Goal Programming Formulation

Each of the three management alternatives had a separate goal

Table 11. The mean allowable cut area per period for different working groups and site classes under the three alternatives

WG [a]	SC [b]	MA [c] one	MA two		MA three	
			MTH [d]	OGH [e]	MTH	OGH
Sb [f]	1	65	50	5	50	1
	2	32	22	4	22	1
Po [g]	2	26	14	5	13	1
Total		123	86	14	85	3

a. WG - Working group;
b. SC - Site class;
c. MA - Management alternative;
d. MTH - Mature timber harvest;
e. OGH - Old-growth harvest;
f. Sb - Black spruce;
g. Po - Poplar.

Table 12. Timber target levels determined by the STELLA model

Period	MA [a] one	MA two	MA three
	-------Timber volume harvested ($100\ m^3$)------		
5	174.8	139.8	117.9
10	182.1	145.9	123.4
15	189.5	152.1	128.9
20	196.8	158.3	134.3
25	200.9	161.7	142.3
30	205.0	165.1	145.5
Total	1149.1	922.9	662.7

a. MA - Management alternative

Table 13. Browse target levels determined by the STELLA model

Period	MA[b] one	MA two	MA three
	----------Dry weight of browse (t)----------		
5	244.5	243.8	243.5
10	243.0	238.5	237.8
15	239.2	231.6	229.4
20	234.9	224.7	220.8
25	231.0	217.8	213.0
30	225.4	210.4	205.8

b. MA - Management alternative

programming solution, but the procedures in formulating three goal models were the same. They varied only in goal target levels and the harvest area constraint. With MA two as an example, the goal programming problem was formulated as follows, based on the target levels determined earlier.

Relative deviations from goals were used as the weights in the objective function. According to Buongiorno and Gilless (1987), if the goal target level is G, the negative deviation is K^-, and the weight is L, the relative deviation from goal can be written as: $(L/G) * K^-$. The relative value of the weight L expresses the relative importance of deviating by one percent from the goal. If the decision makers feel indifferent to a one percent deviation from any of the goals, then this is equivalent to setting all weights equal to 1. The expression of the relative deviation is then: $1/G * K^-$. In this study, for example, the browse goal for the first five year period in MA two is 243.8 tons (Table 13), the relative deviation is $1/243.8B_1^- = 0.0041B_1^-$. The coefficients are very small. In order to avoid a round-off problem, all the coefficients in the equation are multiplied by the same large number to, say 1000, and the relative deviation then becomes $4.10\ B_1^-$. The objective function of the goal programming model was to minimize the negative deviations from goals since the positive deviations are welcome in this case, because maximization of both timber and browse was desired.

$$\text{Minimize } Z = 4.10B_1^- + 4.19B_2^- + 4.32B_3^- + 4.45B_4^- + 4.59B_5^- + 4.75B_6^- + 7.15D_1^- + 6.85D_2^- + 6.58D_3^- + 6.32D_4^- + 6.18D_5^- + 6.06D_6^-$$

Subject to

(1) Timber goal targets (Table 12)

$$Zv1 = \sum_g \sum_i \sum_j A1gij\, X1gij - D1^- + D1^+ = 139.8$$

$$Zv2 = \sum_g \sum_i \sum_j A2gij\, X2gij - D2^- + D2^+ = 145.9$$

.

$$Zv6 = \sum_g \sum_i \sum_j A6gij\, X6gij - D6^- + D6^+ = 165.1$$

(2) Browse goal targets (Table 13)

$$Zb1 = \sum_i \sum_j W1ijNij - B1^- + B1^+ = 243.8$$

$$Zb2 = \sum_i \sum_j W2ijNij + \sum_i WijH1i - B2^- + B2^+ = 238.5$$

.

$$Zb6 = \sum_i \sum_j W6ijNij + \sum_h \sum_i WijHhi - B6^- + B6^+ = 210.4$$

$$\sum_g \sum_i \sum_j Xgij = Hhi$$

(3) Allowable area cut constraints (ha) in the TA zone (Table 11)

$$\sum_j Xh11j \leq 50$$
$$\sum_j Xh12j \leq 22$$
$$\sum_j Xh13j \leq 14$$

(4) Allowable area cut constraints (ha) in the SA zone (Table 11) (h ≥ 2)

$$\sum_j Xh21j \leq 5$$
$$\sum_j Xh22j \leq 4$$
$$\sum_j Xh23j \leq 5$$

(5) Available area (ha) in the TA zone (Appendix 4)

$$\sum_h Xh111 \leq 229$$
$$\sum_h Xh112 \leq 130$$

$$\sum_h Xh1313 \leq 0$$

(6) Available area in the SA zone (Appendix 4)

$$\sum_h Xh211 \leq 77$$
$$\sum_h Xh212 \leq 22$$

$$\sum_h Xh2313 \leq 0$$

(7) Cover area

$$\sum_{h}\sum_{g}\sum_{j=9} X_{hg1j} + \sum_{h}\sum_{g}\sum_{j=10} X_{hg2j} - AR_h = 0$$

$$\sum_{h} CA_h + \sum_{h} AR_h = T_h$$

$A_{hgij} \geq 0$, $B_h^-, B_h^+, D_h^-, D_h^+ \geq 0$

$h = 1, 2, \ldots 6$; $g = 1,2$; $i = 1, 2, 3$; $j = 1, 2, \ldots 13$

where:

D_h^- = negative deviation from the goal of merchantable volume harvested in the hth five year period;

D_h^+ = positive deviation from the goal of merchantable volume harvested in the hth five year period;

B_h^- = negative deviation from the browse production goal in the hth five year period;

B_h^+ = positive deviation from the browse production goal in the hth five year period;

Z_{vh} = total expected merchantable volume harvested in cubic metres at the hth five year period;

Z_{bh} = total amount of browse production in dry weight (kg) at the hth five year period;

A_{hgij} = merchantable volume per ha in hth five year period, gth zone, ith working group, and jth age-class;

X_{hgij} = harvested area in hectares in hth five year period, gth zone, ith working group, and jth age-class;

W_{hij} = dry weight of browse availability per ha in period h, working group i, and age-class j;

N_{ij} = area whose age is less than or equal to 40 years old in ith working group and jth age-class;

H_{hi} = area harvested in period h from working group i;

AR_h = total harvested area in period h from black spruce working group;

CA_h = area available for moose winter cover after harvesting in period h;

Th = total area available in period h for moose winter cover before harvesting.

Goal Programming Solution

The goal model problems were solved by using the Super Lindo packaged program (Schrage 1991) installed on a Macintosh plus computer at Lakehead University. The solutions in Table 14 show the optimal attainment in each period for the different management alternatives. The area which can serve as winter cover for moose by each alternative was listed in Table 15. It shows that if the forest were managed under MA one, regarding timber as the most desired objective, the cover area would be depleted relatively fast. As a result, it may become a limiting factor for moose production potential. Table 16 shows the benefit trade-off or benefit forgone for the three alternatives. What should be pointed out is that the harvest on the sensitive area zone was delayed if the forest were managed by MA

Table 14. GP solutions

objective	period	MA[a] one	MA two	MA three
Gross	5	166.4	130.0	109.4
merchantable	10	173.8	140.9	112.8
volume	15	181.2	147.1	115.6
harvest	20	188.5	153.3	117.7
(100 m^3)	25	192.3	156.7	121.7
	30	196.7	160.1	122.6
	Total	1098.9	888.1	699.8
Browse	5	279.1	279.1	279.1
availability	10	277.8	276.4	276.2
(t)	15	257.8	253.5	252.1
	20	241.3	236.0	232.0
	25	238.4	231.8	224.9
	30	220.4	212.7	202.7

a. MA - Management alternative.

Table 15. Total cover area (ha) predicted for moose

Period	MA[a] one	MA two	MA three
	ha		
5	976	991	991
10	904	922	932
15	817	844	871
20	739	777	825
25	667	717	789
30	685	750	829

a. MA - Management alternative.

Table 16. Benefits trade-off among management alternatives

Benefits	Period	MA[a] one	MA two	MA three
	5	0	36.4	57.0
	10	0	32.9	61.0
Gross	15	0	34.1	65.6
merchantable	20	0	35.2	70.8
timber[b]	25	0	35.6	70.6
(100 m^3)	30	0	36.6	74.1
Total		0	210.8	399.1
	5	0	0	0
Browse	10	0	1.4	1.6
availability[c]	15	0	4.3	5.7
(t)	20	0	5.3	9.3
	25	0	6.6	13.5
	30	0	7.7	17.7
Cover	5	15	0	0
area[d](ha)	10	18	10	0
	15	54	27	0
	20	86	48	0
	25	122	72	0
	30	144	79	0

a. MA - Management alternative.

b. Deviations in gross merchantable timber volume for MA two and MA three from that of MA one at each period, based on the data in Table 14

c. Deviations in dry weight of browse for MA two and MA three from that of MA one at each period, based on the data in Table 14

d. Deviations in cover area for MA one and MA two from that of MA three at each period, based on the data in Table 15 two or MA three. This operation was to conserve old-growth area for aesthetic purposes; consequently, the timber volume harvested and the browse availability would decrease, but the cover area would increase, and the aesthetic value would be higher compared to MA one. The forest manager could obtain an impression of gains or losses by implementing the different management alternatives from the data in Table 16. For example, if the manager wants to take outdoor recreation into consideration, he should conserve the old-growth area in the SA zone, and manage the forest stands by MA two or MA three. He should realize from Table 16 that he would lose 21080 m^3 or 39910 m^3 in timber yield and also lose some production of moose browse in the 30-year period of management. The loss will be compensated for by increasing moose cover and old-growth reserves in the SA zone in order to increase the aesthetic value.

The solutions show that the optimal allocation of the study area, as a result of the goal programming application, imply the possibility that conflicts among the interest groups would be minimized by the means of integrated forest management.

CONCLUSION AND SUGGESTION

How to manage forest resources is a challenging issue forest managers are facing today. As society places more demands on the forest, a larger number of interest groups will become involved in forest resource management problems. Modern resource management problems are characterized by conflicting and competitive demands for uses of forest resources. It is hoped that all the functions of the forest resources can be brought into full play in order to meet the needs of every group as much as possible.

This study attempted to handle the complex resource management problem in a feasible way. It also looked at an approach encompassing the various land use problems that occur on the forest lands. The analytical tool developed for this purpose used two different modelling approaches: the system dynamic model (STELLA) which helps us to develop our understanding of forest dynamic behaviour, and the goal programming model which makes a management plan in a specific way under the guidance of simulation results from the STELLA model. The two types of models were linked to allow the advantages of two models to complement each other. Through this approach, rationality and optimality of the management plan can be achieved.

Through the function of feedback loops, the STELLA model monitored the distribution of the age-classes or habitats, and the harvest area was decided based on this distribution. If the forest were at the ageing state, that is, most of the stands became mature or old, the harvest area decided by the model would be 1.3 times as much as that decided by the conventional normal area control formula, *total area/rotation age*. On the other hand, if the forest were dominated by young stands, the model could set the harvest area as low as zero. The model adjusted the distribution of the age-classes until it reached a steady state. During the adjustment, the harvest area varies from period to period. The situation seems to violate the principle of sustained yield. In fact, the STELLA model could guide forests into a theoretical normal state in a smoother way than the simple area control models, and the forests would reach a normal state earlier by the STELLA model than by other models. Taking this study as an example, the model could bring the study area to reach an approximate steady (normal) state in about 80 years (Tables 6, 7, and 8), below the current rotation age.

The goal programming solution was greatly improved by the enhanced target levels, which were objectively determined by the simulation results of the STELLA model. The target levels for the GP model are often difficult for the decision makers to specify since their determination needs sufficient knowledge of the decision environment (Mendoza 1986). Walker (1985) developed a procedure to determine target levels. His approach identifies both the feasibility space and the optimal policy space for each objective by using linear programming models. However, if the allowable cut area is unknown, or if the area control formula were used to calculate the allowable cut area in the linear model (Davis and Johnson 1987; Buongiorno and Gilless 1987), the target level determined by Walker's method might still not be reasonable. This problem can be effectively solved by using the STELLA model.

The resource manager may not be satisfied with this system, since the timber harvest decreased substantially. However, the plan was made based on the principle of multiple-use and sustainable yield. In this study, since the stands in the study area were distributed unevenly among age-classes with the seedling habitat making up 37 percent of the total area (Figure 16 and Table 2), the plan has to delay harvesting operations in the first few years in order to protect the resources and environment from deterioration.

Although the study area is very small, it has revealed some problems if multiple use management instead of timber management was practiced in the Spruce River Forest or any similar forest area in Ontario. If multiple use management is implemented, the following suggestions are put forward:

1. The Abitibi-Price Spruce River management unit covers a vast amount of area. The total productive area is 623,122 ha. The management strategy, timber or multiple use, may not be the same for the total area. Besides following the principle of sustainable yield, the forest resource managers could pay more attention to non-timber benefits, such as wildlife, aesthetics, and recreation, especially in these areas near the community of Thunder Bay.

2. The whole management unit could be further divided into working compartments, so that management plans could apply to each compartment. In this way, the age-classes would be more evenly distributed in the area. Otherwise, a management plan for the whole area would result in a situation such that the age-classes are well distributed from the view of the whole management unit, but this would not be from the view of the small compartment, just as the case in this study.

3. The species composition would need to be changed to consider forest scenic beauty. If the resource manager wants to increase the aesthetic value in the area, especially in the sensitive area (SA) zone, some long-life span species, such as pines, cedar, etc., should be used to replace the short-life span species in part of the area in the SA zone. In this way, old-growth reserves in the SA zone can be conserved for a longer time and scenic beauty can be increased.

This study tried to solve the problems of integrated forest resource management by means of combining two models. Integrated resource management is a complicated issue, and many problems in this field remain to be solved. There are numerous studies on this issue, but few successful cases in practice. This situation must be changed through efforts made by various groups in society. Only by way of multiple-use, can forest resources be managed to meet the needs of man. So, it is my hope that the techniques demonstrated in this paper could arouse some interests in researchers in this field, and have some value for consideration by the forest resource manager.

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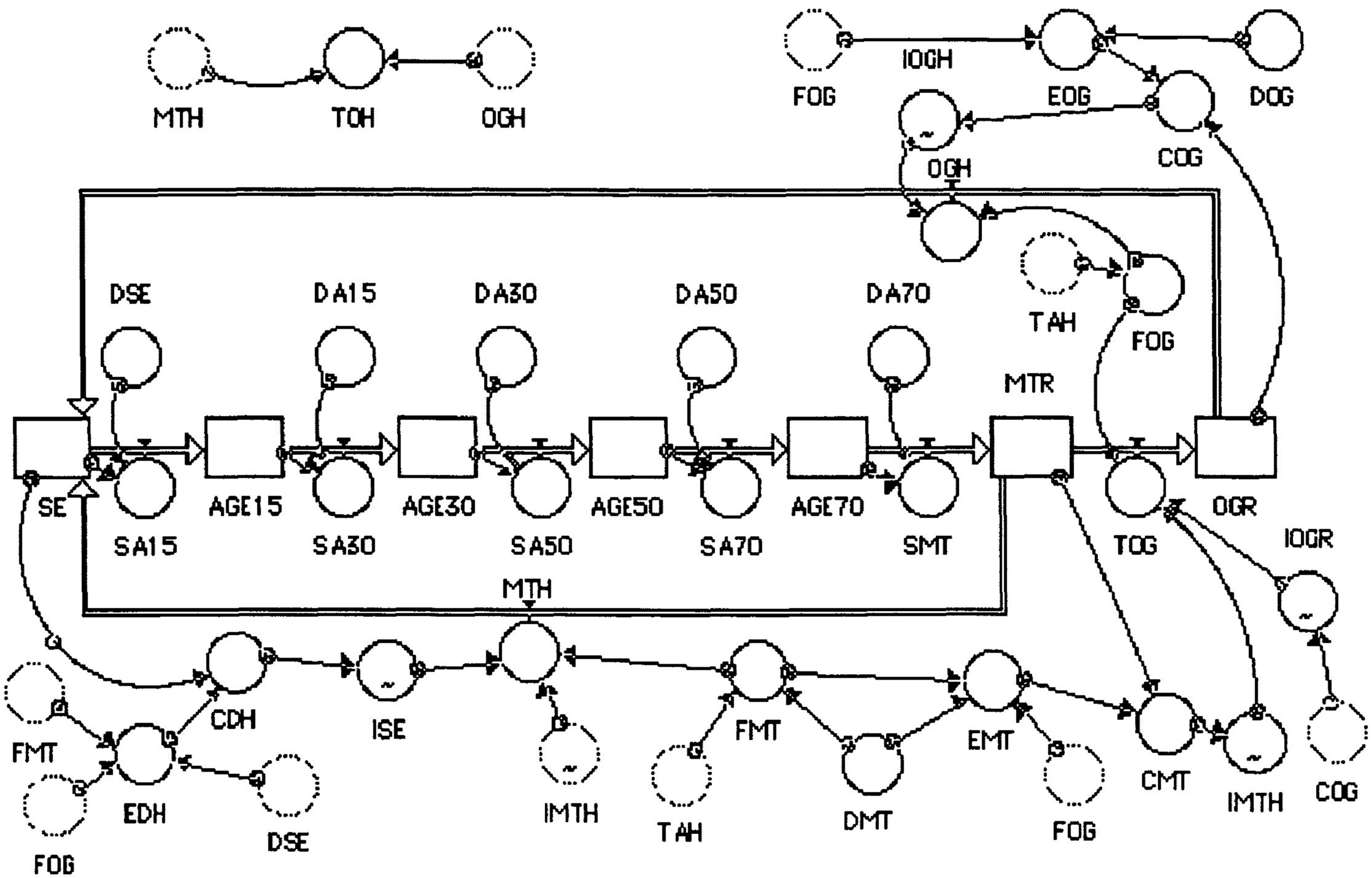
APPENDIX 1

THE FLOW DIAGRAM OF THE INFORMATION NETWORK FOR THE STELLA MODEL



(see next page for definition of the symbols)

Definitions of symbols for the diagram of the STELLA model (in alphabetical order)

AGE15 - Area of age-class 11-20 years (ha)

AGE30 - Area of age-class 21-40 years (ha)

AGE50 - Area of age-class 41-60 years (ha)

AGE70 - Area of age-class 61-80 years (ha)

CDH - Coverage of seedling habitat (dimensionless)

CMT - coverage of mature habitat (dimensionless)

COG - Coverage of old-growth habitat (dimensionless)

DA15 - Delay for age-class 11-20 years succession (years)

DA30 - Delay for age-class 21-40 years succession (years)

DA50 - Delay for age-class 41-60 years succession (years)

DA70 - Delay for age-class 61-80 years succession (years)

DMT - Delay for mature habitat succession (years)

DOG - Delay for old-growth succession (years)

DSE - Delay of seedling habitat succession (years)

EDH - Equilibrium seedling habitat (ha)

EMT - Equilibrium mature timber reserves (ha)

EOG - Equilibrium old-growth reserves (ha)

FMT - Flow rate of succession to mature timber habitat (ha/year)

FOG - Flow rate of succession to old-growth reserves (ha/year)

IMTH - Indicated mature timber harvest (dimensionless)

IOGH - Indicated old-growth harvest (dimensionless)

IOGR - Indicated mature timber reserves (dimensionless)

ISE - Indicated seedling habitat (dimensionless)

MTH - Mature timber harvested (ha/year)

MTR - Mature habitat reserves (ha)

OGH - Old-growth harvest (ha/year)

OGR - Area of old-growth reserves (ha)

SA15 - Succession to age-class 11-20 (ha/year)

SA30 - Succession to age-class 21-40 (ha/year)

SA50 - Succession to age-class 41-60 (ha/year)

SA70 - Succession to age-class 61-80 (ha/year)

SE - Seedling habitat (ha)

SMT - Succession to mature timber habitat (ha/year)

TAH - Total area of all age-classes and habitats (ha)

TOG - Transfer rate from mature timber to old-growth reserves (ha/year)

TOH - Total area harvested (ha/year)

APPENDIX 2

STELLA MODEL EQUATIONS FOR MANAGEMENT ALTERNATIVE ONE

□ AGE15 = AGE15 + dt[3] * (SA15 - SA30)
INIT[4] (AGE15) = 340

□ AGE30 = AGE30 + dt * (SA30 - SA50)
INIT(AGE30) = 165

□ AGE50 = AGE50 + dt * (SA50 - SA70)
INIT(AGE50) = 84

□ AGE70 = AGE70 + dt * (SA70 - SMT)
INIT(AGE70)= 560

□ MTR = MTR + dt * (SMT - TOG - MTH)
INIT(MTR)= 692

□ OGR = OGR + dt * (TOG - OGH)
INIT(OGR) = 0

□ SE = SE + dt * (- SA15 + MTH + OGH)
INIT(SE) = 1097

○ API = VSE*VPOG*VBAL

○ BAL = HT2/HT1

○ CDH = SE/EDH

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3. dt - Delta time (one year in this study)
4. INIT - Initial area

CMT	= MTR/EMT
COG	= OGR/EOG
DA15	= 10
DA30	= 20
DA50	= 20
DA70	= 20
DMT	= 10
DOG	= 0
DSE	= 10
EDH	= (FMT+FOG)*DSE
EMT	= (FOG+ FMT)*DMT
EOG	= FOG*DOG
FMT	= TAH/(DSE+DA15+DA30+DA50+DA70+DMT)
FOG	= (TAH*0)/(DSE+DA15+DA30+DA50+DA70+DMT+DOG)
HAMT	= (MTR/FMT)+80
HAOG	= (OGR/FOG)+80+DMT
HT1	= SE+AGE15+AGE30+AGE50
HT2	= AGE70+MTR
MPI	= SQRT(IL20*IG20)
MTH	= (MIN(ISE,IMTH))*FMT
OGH	= IOGH*FOG
PG20	= TG20/TAH

PL20 = TL20/TAH

POG = OGR/TAH

PSE = SE/TAH

SA15 = SE/DSE

SA30 = AGE15/DA15

SA50 = AGE30/DA30

SA70 = AGE50/DA50

SMT = AGE70/DA70

TAH = MTR+OGR+AGE70+AGE50+AGE30+AGE15+SE

TG20 = OGR+MTR+AGE70+AGE50+AGE30

TYM = (TAH/TMR)*TYR

TL20 = AGE15+SE

TMR = 90

TOG = (MIN(IOGR, IMTH))*FOG

TPI = (TVO+TVM)/TYM

TVM =MTH*MTYR

TVO = OGYR*OGH

ISE = graph(CDH)
(0.0,1.30),(0.500,1.30),(1.00,1.00),(1.50,0.698),
(2.00,0.398),(2.50,0.0975),(3.00, 0.0)

IG20 = graph(PG20)
(0.0,0.0),(0.0500,0.135),(0.100,0.270),(0.150,0.405),
(0.200,0.540),(0.250,0.670),(0.300,0.830),(0.350,1.00),
(0.400,1.00),(0.450,1.00),(0.500,1.00),(0.550,1.00),
(0.600,0.885),(0.650,0.770),(0.700,0.660),(0.750,0.540),
(0.800,0.425),(0.850,0.305),(0.900,0.190),

(0.950,0.0900),(1.00, 0.0)

IL20 = graph(PL20)
(0.0,0.0),(0.100,0.260),(0.200,0.500),(0.300,0.755),(0.400,1.00),
(0.500,1.00),(0.600,0.805),(0.700,0.590),(0.800,0.385),
(0.900,0.195),(1.00, 0.0)

IMTH = graph(CMT)
(0.500, 0.0),(1.00,1.00),(1.50,1.10),(2.00,1.20),(2.50,1.30)

IOGH = graph(COG)
(0.500, 0.0),(1.00,1.00),(1.50,1.10),(2.00,1.20),(2.50,1.30)

IOGR = graph(COG)
(0.0,1.30),(0.500,1.30),(1.00,1.00),(1.50,0.698),(2.00,0.398),
(2.50,0.0975),(3.00, 0.0)

MTYR = graph(HAMT)
(60.0,0.340),(80.0,0.680),(100,1.00),(120,1.20),(140,1.29),(160,1.32),
(180,1.32),(200,1.32)

OGYR = graph(HAOG)
(60.0,0.340),(80.0,0.680),(100,1.00),(120,1.20),(140,1.29),(160,1.32),
(180,1.32),(200,1.32)

TYR = graph(TMR)
(60.0,0.340),(80.0,0.680),(100,1.00),(120,1.20),(140,1.29),(160,1.32),
(180,1.32),(200,1.32)

VBAL = graph(BAL)
(0.0,0.400),(0.500,0.700),(1.00,1.00),(1.50,0.700),(2.00,0.400)

VPOG = graph(POG)
(0.0,0.400),(0.1000,0.700),(0.200,0.900),(0.300,1.00),(0.400,0.900),
(0.500,0.800),(0.600,0.600),(0.700,0.400)

VSE = graph(PSE)
(0.0400,0.200),(0.0617,0.600),(0.0833,0.900),(0.105,1.00),(0.127,0.900),
(0.148,0.600),(0.170,0.200)

APPENDIX 3

STELLA MODEL EQUATIONS FOR MANAGEMENT ALTERNATIVE TWO AND THREE

□ AGE15 = AGE15 + dt[5] * (SA15 - SA30)
INIT[6] (AGE15) = 340

□ AGE30 = AGE30 + dt * (SA30 - SA50)
INIT(AGE30) = 165

□ AGE50 = AGE50 + dt * (SA50 - SA70)
INIT(AGE50) = 84

□ AGE70 = AGE70 + dt * (SA70 - SMT)
INIT(AGE70)= 560

□ MTR = MTR + dt * (SMT - TOG - MTH)
INIT(MTR) = 598

□ OGR = OGR + dt * (TOG - OGH)
INIT(OGR) = 94

□ SE = SE + dt * (-SA15 + MTH + OGH)
INIT(SE) = 1097

○ API = VSE*VPOG*VBAL

○ BAL = HT2/HT1

○ CDH = SE/EDH

○ CMT = MTR/EMT

○ COG = OGR/EOG

○	DA15	= 10
○	DA30	= 20
○	DA50	= 20
○	DA70	= 20
○	DMT	= 10
○	DOG	= 40 (80)*
○	DSE	= 10
○	EDH	= (FMT+FOG)*DSE
○	EMT	= (FOG+ FMT)*DMT
○	EOG	= FOG*DOG
○	FMT	= (TAH* (1- 0.3))/(DSE+DA15+DA30+DA50+DA70+DMT)
○	FOG	= (TAH* 0.3)/(DSE+DA15+DA30+DA50+DA70+DMT+DOG)
○	HAMT	= (MTR/FMT)+80
○	HAOG	= (OGR/FOG)+80+DMT
○	HT1	= SE+AGE15+AGE30+AGE50
○	HT2	= AGE70+MTR
○	MPI	= SQRT(IL20*IG20)
○	MTH	= (MIN(ISE,IMTH))*FMT
○	OGH	= IOGH*FOG
○	PG20	= TG20/TAH
○	PL20	= TL20/TAH
○	POG	= OGR/TAH

PSE = SE/TAH

SA15 = SE/DSE

SA30 = AGE15/DA15

SA50 = AGE30/DA30

SA70 = AGE50/DA50

SMT = AGE70/DA70

TAH = MTR+OGR+AGE70+AGE50+AGE30+AGE15+SE

TG20 = OGR+MTR+AGE70+AGE50+AGE30

TYM = (TAH/TMR)*TYR

TL20 = AGE15+SE

TMR = 90

TOG = (MIN(IOGR, IMTH))*FOG

TPI = (TVO+TVM)/TYM

TVM = MTH*MTYR

TVO = OGYR*OGH

ISE = graph(CDH)
(0.0,1.30),(0.500,1.30),(1.00,1.00),(1.50,0.698),
(2.00,0.398),(2.50,0.0975),(3.00, 0.0)

IG20 = graph(PG20)
(0.0,0.0),(0.0500,0.135),(0.100,0.270),(0.150,0.405),
(0.200,0.540),(0.250,0.670),(0.300,0.830),(0.350,1.00),
(0.400,1.00),(0.450,1.00),(0.500,1.00),(0.550,1.00),
(0.600,0.885),(0.650,0.770),(0.700,0.660),(0.750,0.540),
(0.800,0.425),(0.850,0.305),(0.900,0.190),
(0.950,0.0900),(1.00, 0.0)

IL20 = graph(PL20)
(0.0,0.0),(0.100,0.260),(0.200,0.500),(0.300,0.755),(0.400,1.00),
(0.500,1.00),(0.600,0.805),(0.700,0.590),(0.800,0.385),

(0.900,0.195),(1.00, 0.0)

IMTH = graph(CMT)
(0.500, 0.0),(1.00,1.00),(1.50,1.10),(2.00,1.20),(2.50,1.30)

IOGH = graph(COG)
(0.500, 0.0),(1.00,1.00),(1.50,1.10),(2.00,1.20),(2.50,1.30)

IOGR = graph(COG)
(0.0,1.30),(0.500,1.30),(1.00,1.00),(1.50,0.698),(2.00,0.398),
(2.50,0.0975),(3.00, 0.0)

MTYR = graph(HAMT)
(60.0,0.340),(80.0,0.680),(100,1.00),(120,1.20),(140,1.29),(160,1.32),
(180,1.32),(200,1.32)

OGYR = graph(HAOG)
(60.0,0.340),(80.0,0.680),(100,1.00),(120,1.20),(140,1.29),(160,1.32),
(180,1.32),(200,1.32)

TYR = graph(TMR)
(60.0,0.340),(80.0,0.680),(100,1.00),(120,1.20),(140,1.29),(160,1.32),
(180,1.32),(200,1.32)

VBAL = graph(BAL)
(0.0,0.400),(0.500,0.700),(1.00,1.00),(1.50,0.700),(2.00,0.400)

VPOG = graph(POG)
(0.0,0.400),(0.1000,0.700),(0.200,0.900),(0.300,1.00),(0.400,0.900),
(0.500,0.800),(0.600,0.600),(0.700,0.400)

VSE = graph(PSE)
(0.0400,0.200),(0.0617,0.600),(0.0833,0.900),(0.105,1.00),(0.127,0.900),
(0.148,0.600),(0.170,0.200)

* The only difference between equations for two alternatives is in DOG,40 years for management alternative two, and 80 years for management alternative three.

APPENDIX 4

INVENTORY LISTINGS OF THE TIMBER AREA AND THE SENSITIVE AREA ZONE

	TA[a] zone			SA[b] zone		
	Sb WG[c]		Po WG[d]	Sb WG		Po WG
Age class	SC[e] 1	SC 2	SC 2	SC 1	SC 2	SC 2
	ha					
0 - 5	229	33	0	77	35	0
6 - 10	130	134	233	22	127	77
11 - 15	32	177	0	33	0	16
16 - 20	60	0	0	22	0	0
21 - 25	11	90	0	0	24	0
26 - 30	0	0	0	0	32	0
31 - 35	0	0	0	0	0	0
36 - 40	0	0	0	0	0	8
41 - 60	57	0	10	17	0	0
61 - 80	171	48	63	118	5	155
81 - 100	468	46	19	8	5	52
101 - 120	6	4	4	0	0	0
120+	76	4	0	0	0	0
Total	1240	536	329	305	228	300

a TA - Timber area

b. SA - Sensitive area

c. Sb WG - Black spruce working group

d. Po WG - Aspen working group

e. SC - Site class