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FILE REPORT 45

Computer Simulation and Economic Imlications of Traditional Clearcut and Alternate Silviculture Forest Management Strategies in Northwastern Ontario's Boreal Forest

T. Gooding, L. Van Damme and M. Carlson

Natural Resources Canada / Ressources naturelles Canada
Canadian Forest Service / Service canadien des forêts

Ministry of Natural Resources / Ministère des Richesses naturelles
Ontario

"Economic wood supply from alternative silvicultural systems"

This file report is an unedited, unpublished report submitted as partial fulfilment of NODA/NFP Project #4218, "Computer simulation and economic implications of Traditional clearcut and alternative silviculture forest management strategies in Northwestern Ontario's boreal forest".

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COMPUTER SIMULATION AND ECONOMIC IMPLICATIONS OF TRADITIONAL CLEARCUT AND ALTERNATIVE SILVICULTURE FOREST MANAGEMENT STRATEGIES IN NORTHWESTERN ONTARIO'S BOREAL FOREST

T. Gooding[1], L. Van Damme[2] and M. Carlson[3]

[1]Senior resource analyst, Pearson Timberline Forestry Consultants, Suite 315, 10357-109th St., Edmonton, Alberta. Phone: (403) 425-8826. FAX: (403) 428-6782. E-mail: elg@tfic.bc.ca

[2]Consulting forester, KBM Forestry Consultants Inc., 349 Mooney Ave., Thunder Bay, Ontario. Phone: (807) 345-5445. FAX: (807) 345-5858. E-mail: laird.vandamme@lakeheadu.ca

[3]Research assistant , KBM Forestry Consultants Inc., 349 Mooney Ave., Thunder Bay, Ontario. Phone: (807) 345-5445. FAX: (807) 345-5858.

ACKNOWLEDGEMENTS

This report and the background work to develop it would not have been possible without the financial support of the Northern Ontario Development Agreement between Natural Resources Canada, Canadian Forestry Service and the Ontario Ministry of Natural Resources. In addition, the digital files and the permanent sample plot information necessary for the development of the data sets were provided by Abitibi Consolidated in Fort Frances, Ontario.

The authors would also like to acknowledge the input of Dr. Peter Duinker, Dr. Reino Pulkki, Dr. Jeremy Williams, Sandy Gordon, Colin Hewitt, Dave Legg and Nancy Bookey.

ABSTRACT

This report describes predictions of the forest structure and the timber supply derived from alternative silvicultural systems compared to clearcut silvicultural systems. A modified computer simulation model (Harvest Schedule Generator 3.0) was used to generate 200-year forecasts for a case-study northwestern Ontario site. This comparative analysis was done to provide insight for forest managers considering the implementation of alternative silvicultural systems. Alternative systems were found to produce lower long term sustained yields and required more forested area per cubic meter of harvest compared to clearcut systems. The study also compared volume-based harvest scheduling rules to economic-based harvest scheduling rules. Economic-based rules exhibited greater overall economic efficiency. The study also found that harvest levels below the maximum long-term sustained yield were more profitable for the land owner and the timber operator. The implications of this work suggest that forest managers should favour a conservative harvest level, especially when wood product prices are low.

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1.0 INTRODUCTION

The practice of forestry is evolving towards a phase of greater social responsibility. This socially responsible forestry has been referred to as "new forestry" (Kimmins 1992). In new forestry, forest management activities are tempered by and adapt to society's evolving perception of what constitutes proper stewardship. Consequently, ecosystem management and objectives such as maintenance of biological diversity (biodiversity) (Sampson and Knof 1982; Hunter 1990; Kimmins 1992) are now mandated in many jurisdictions. Part of new forestry is an increased use of alternative silvicultural systems over traditional systems based on clearcutting and artificial regeneration (Kimmins 1992).

Over the previous two decades there has been a tremendous emphasis upon clearcut silvicultural systems that rely upon tree planting to assure successful conifer regeneration (Anon. 1993; Hearnden *et al.* 1993; Koven and Martel 1994). The high cost of tree planting, coupled with perceptions of the ecological consequences of large-scale clearcutting and planting, have made clearcut systems a public concern (Kimmins 1992; Dodds 1994; Carlton 1995; Reed 1995; Ulley 1995). For example, international attention upon clearcutting in British Columbia's Clayoquot Sound resulted in significant reductions in the area scheduled for harvesting and the introduction of alternatives to clearcutting such as green tree retention (Beese and Dunsworth 1994; Reed 1995; Lewis 1995). In Ontario, international pressure has been less intense, but recent government initiatives aimed at reducing the traditional level of clearcutting and artificial regeneration have been introduced (OMNR 1993b; Koven and Martel 1994; Boast 1995). As a result, alternatives to clearcut silvicultural systems are now receiving greater levels of interest across Canada (Koven and Martel 1994; Alberta Pacific Forest Industries 1996). Recently, studies have been initiated to determine the impacts of alternative silvicultural systems (see Jeglum and Kennington 1993; Yang and Bella 1994; Arnott *et al.* 1995; Navratil *et al.* 1994; Rollins *et al.*1995; Alberta Pacific Forest Products 1996; Lieffers *et al.* 1996). However, these are all stand-level studies that fail to take forest-level dynamics into account.

In new forestry, it is not a matter of whether alternatives to traditional silvicultural systems will be applied, but rather to what degree. Faced with public pressure for change, there is a requirement to make reasonable predictions about the effects of alternative silvicultural systems upon both the forest structure and the goods derived from them (Ontario Forestry Policy Panel 1993; Dodds 1994). Due to the long time required to demonstrate the pros and cons of new forestry, the probable consequences should be explored in the interim by using computer simulation models (Kimmins 1992).

The objective of this study is to examine the long-term, timber supply consequences of applying alternative silvicultural systems in boreal forests of northwestern Ontario. This was accomplished by comparing the predicted results from a range of forest management strategies. The predicted results were generated from a modified forest planning computer model, the Harvest Schedule Generator (HSG), developed by Moore and Lockwood (1990). Using the modified model, 200-year forecasts were developed for both a case-study northwestern Ontario forest and some hypothetical forest structures.

Throughout this report HSG commands are in CAPITAL letters and HSG terms are in *italics*.

2.0 SILVICULTURAL SYSTEMS

Clearcut harvesting of upland forest mixed wood types tends to favour the regeneration of hardwood species that are capable of vegetative reproduction. This results in a different forest structure after harvest than that produced by natural conditions such as fire (Hearnden *et al.* 1993). This situation applies to Ontario's boreal forest. To maintain the conifer component, clearcut harvest areas were planted or seeded in the 1980's. Site preparation or tending was often required to ensure conifer regeneration (Koven and Martel 1994).

Other techniques can be used to maintain the conifer component in the boreal forest (Wedeles *et al.* 1995). These techniques involve changing not only the method of regeneration, but also the entire approach to harvesting and stand renewal. Taken together these methods comprise a silvicultural system. According to Wedeles *et al.* (1995) and the Canadian Forest Service (1995), silvicultural systems are identified by the cutting method with which the regeneration is established. Silvicultural systems can be divided into the following categories (Wedeles *et al.* 1995): Clearcutting system, Modified Clearcutting System (which is further broken down into Strip Clearcutting System, Seed Tree System, and Multiple entry Harvesting System), Shelterwood System and Selection System.

For this study, the term "alternative silvicultural system" refers to all silvicultural systems other than those using clearcutting. These systems are considered alternative only because clearcutting has been the dominant and traditional silvicultural system employed in the boreal forests of Ontario since the beginning of this century (Wedeles *et al.* 1995).

Other than strip clearcutting, there is little experience with the application of alternative silvicultural systems in northwestern Ontario's boreal forest (Wedeles *et al.* 1995). Therefore, potential impacts of alternative silvicultural systems must be derived from a combination of the limited local data with results achieved in other areas. Potential prescriptions for alternative silvicultural systems in Ontario's boreal forest can thus be developed from prescriptions of similar techniques to similar ecosystems, tempered with assumptions from local experience.

2.1 SYSTEM DEFINITIONS

2.1.1 Clearcutting

The clearcutting system removes all economically merchantable trees from a site in one pass. Any appropriate method of natural or artificial regeneration may be applied after harvest. Natural regeneration refers to natural seeding, sprouting, suckering, or layering while artificial regeneration refers to direct seeding or the planting of seedlings or cuttings (Canadian Forest Service 1995).

2.1.2 Modified Clearcutting Systems

The seed tree system resembles the clearcutting system in that all merchantable trees are removed except for a small number of trees that are left as a seed source. The intent is to establish a naturally regenerated even-aged stand.

In the strip clearcutting system, the harvest pattern is defined spatially within each harvest area. Alternating strips of residual unharvested and clearcut harvested strips are applied to the harvest areas. A modification on this theme is block cutting where the harvest zone is broken into clearcut and leave blocks. Natural regeneration is derived from seed from trees in the residual strips or blocks, although the residual strips may require artificial regeneration once they are harvested (Jeglum and Kennington, 1993).

Multiple entry harvesting includes two and three-phase harvesting designed to manipulate a stands vertical structure. Multiple entry harvesting can involve the removal of an overstory to release an understory species (e.g. Aspen over White Spruce) (Lieffers *et al.* 1996). Multiple entry harvesting can also be associated with the practice of careful logging around advanced growth (CLAAG) of the same species in the understory (e.g. black spruce) (Groot 1984).

Multiple entry harvesting might also be a suitable classification for a harvest pattern designed to extend the "life" of a forested stand by cutting trees of poor vigor and/or creating growing space for residual trees. This is very similar to the practice of salvage thinning that is currently being investigated by at least one company operating in Canada's boreal forest (Jamieson, 1997)). These silvicultural systems could be part of a strategy to avoid shortfalls in long run sustained yield expected from forests that are dominated by older age classes.

2.1.3 Shelterwood

The shelterwood system harvests the stand in a series of cuts separated by short time intervals. The goal is to establish even-aged natural reproduction under the protective cover of mature trees. This system is useful for species that suffer from exposure related damage (e.g. frost) and can be spatially applied in a uniform, irregular or strip pattern (Wedeles *et al.* 1995).

2.1.4 Selection

The selection system is defined as a method of regenerating a forest stand and maintaining an uneven-aged structure by removing some trees in all size classes over the entire area either singly or in small groups or strips (Canadian Forest Service 1995). This results in a forest with a continuous series of age classes and allows mortality and harvesting to be balanced by new growth and recruitment. In this manner, a constant and sustainable timber yield is achieved (Wedeles *et al.* 1995). The selection system is useful when forest cover, stand structure and species diversity must be maintained for environmental and/or economic reasons. The selection harvest is distinguishable from selective cutting by the care taken in selection to maintain horizontal and vertical stand structure (Wedeles *et al.* 1995). A selective harvest, on the other hand, is used to remove trees from only certain species, quality, and/or size classes (i.e. high-grading).

2.2 APPLICATION OF SILVICULTURE SYSTEMS

Alternative silvicultural systems have greater limitations to the range of biophysical conditions under which they can be successfully applied compared to clearcut systems.

structure. These prescriptions are based upon stand-level biological growth criteria and economic demand. As a result, silvicultural ground rules consider the biological capacity of the site mostly in reference to producing timber (Koven and Martel 1994).

At the stand-level, the fibre-maximizing harvest age is the stand age where the current annual increment (CAI) equals the mean annual increment (MAI) (Smith 1986; Davis and Johnson 1987). However, at the forest-level, objectives such as even-flow will usually require deviations from the optimum harvest age. As a result, it is necessary either to alter the age at which some of the stands are harvested and perhaps, to engage in non-optimal silvicultural treatments, or to relax the forest-level objectives. This clearly shows the forest manager's dilemma - which objectives should be relaxed and which sub-optimal treatments should be applied to produce the best possible combination of activities resulting in the most desirable outcome for the whole forest? A desirable solution cannot be determined until the forest manager can predict the outcome of different management regimes upon the whole forest (Baskerville 1986; Willcocks *et al.* 1990). Forest-level models have been developed specifically as a decision support tool to aid the forest manager in solving this dilemma (e.g. Moore *et al.* 1994).

Testing forest management alternatives with forest planning models is gaining wider acceptance. The Forest Management Planning Manual for Ontario's Forests (OMNR 1995) requires the use of a forest-level planning model in the planning process. Furthermore, the manual stipulates that the model must be used in an adaptive management framework to predict the outcome of a range of management alternatives.

These legislative requirements have stimulated the practical application of forest planning models.

3.0 METHODS

3.1 CASE STUDY AREA: THE SEINE RIVER FOREST

The Seine River Forest (SRF) is located approximately 200 kilometers north-west of Thunder Bay and 100 kilometers east of Fort Frances, Ontario (Figure 1). This forest is Crown land managed by Abitibi Consolidated under a Forest Resource License (Legislative Assembly of Ontario 1994). The forest is largely within the transition zone between the Boreal and Great Lakes-St. Lawrence forests (Rowe 1972).

Like many boreal forests in Ontario, the distribution of age classes in the SRF is unbalanced. The majority of the productive forest area falls in the 60-to-90 year range (Figure 2). The growing stock volume in the SRF is composed primarily of three species: jack pine ((Pj) *Pinus banksiana* Lamb.), black spruce ((Sb) *Picea mariana* (Mill.) B.S.P.) and poplar ((Po) *Populus tremuloides* Michx.) (Figure 3). The six remaining species make up only a small percentage of the total volume.

3.2 MODEL SELECTION.

A personal computer version of Moore and Lockwood's (1990) Harvest Schedule Generator (HSG)[1] was the forest planning model chosen for this study because of its spatially referenced capacity, readily available source code and operating environment.

[1] The PC version of HSG is distributed by Dendron Resource.

Due to the detailed information contained within the inventory file, HSG is well suited to model alternative silvicultural systems such as selection, seed tree, multi-pass and shelterwood. The results of these systems' activities upon the stand's biophysical structure can be represented by changes in the stand's components listed within the inventory.

A 1991 Forest Resource Inventory of the Seine River Forest (SRF) was supplied by Abitibi Consolidated. The spatial inventory used in this study originated on Abitibi Consolidated's ARC/INFO system. The inventory was converted to a grid format (200 X 200 m cells) required by HSG. This conversion resulted in the loss of almost 1000 of the 8000 polygons in the inventory, which is equivalent to less than 4% of the area. This reduced forest inventory consisting of 7093 polygons was the inventory used in the simulations.

3.3 HSG MODIFICATIONS: VERSION 3.0

Three major changes were made to the HSG source code for this study. First, a method was developed to permit partial harvesting. Second, a new harvest priority rule using economic harvest and regeneration parameters was added. Third, changes were made to the output files to track the previous changes. The modified version is referred to as HSG 3.0.

3.3.1 Multiple entry Harvesting

HSG was initially designed to support the clearcutting of whole stands. Although it contained information on individual stand components, it had no mechanism of harvesting these components individually. The HSG model was modified to allow the harvest of portions of individual stand components, to simulate the impact of the partial harvesting used in alternative silvicultural systems. The harvest changes consist of two new multiple entry harvest functions and the addition of modifiers to apply additional control over stands eligible for harvest (Gooding 1997).

The multiple entry harvesting algorithm was designed to mimic the harvesting patterns resulting from multiple entry harvesting. These techniques remove a portion of a stand and are usually fairly evenly distributed throughout the stand. Block or strip harvesting is not well represented by the new multiple entry harvesting algorithm in that forest polygons are never changed during the simulation runs.

Alternative silvicultural systems are applicable to a narrower range of biophysical conditions than clearcutting. Therefore, HSG 3.0 was designed to permit the use of two harvest priority rule modifiers. One modifier is the *Harvest Allocation List* (HAL) used to restrict harvesting to a user-defined range of working group conditions. The second modifier created was the *harvest protection period* (HPP). The *harvest protection period* is an optional user-defined value that may be applied to each harvest priority rule to protect stands from harvest for a specified time period. The *harvest protection period* can be used to protect a stand from harvest until desirable stand conditions are established. Alternatively it can be used in conjunction with the *state table* and harvest rules to "hold" a stand within a range of conditions while multiple entry harvesting is conducted upon the stand at regular intervals (Gooding 1997).

3.3.2 Economic Harvest Priority Rules

The source code for HSG was expanded to utilize and report upon economic criteria. A new harvest priority rule (Rule_3) was added. Rule_3 ranks stands for harvest by calculating an annual average 10-year opportunity cost of harvest delay for each stand (Armstrong *et al.* 1992). Stands with the highest opportunity cost are ranked at the top of the queue. Harvesting commences from the top of the list and continues until the targets are satisfied or the list of eligible stands is exhausted. Rule_3 calculates the opportunity cost of harvest delay using equation [1].

Since economic variables are now present in the harvest rule, a new optional *economic operability minimum* was included. A rational profit-maximizing forest manager would not harvest stands with a negative economic return[2] (i.e. stands that cost more to harvest than the total value of their products). Rule_3 was designed to give the user the option to set an *economic operability minimum*, for which the stand's Residual Timber Value (RTV) must be greater than or equal to the minimum for it to be eligible for harvest. RTV is calculated as Price (P) – Cost (C) – Transportation Cost (M) and can be used as a measure of economic profit. This function is applied globally and loaded through the *ECONOMIC* command. Gooding (1997) provides a detailed account of the various features of HSG 3.0.

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[2] There are exceptions. Harvesting stands with a negative economic return would be considered for stand conversions, or harvesting poor quality or damaged stands (e.g. fire, insect damage) in order to replace with a higher quality stand.

3.4 MODEL CALIBRATION

3.4.1 Volume Curve Development

Time-dependent pure-species volume curves, adjusted for site conditions, are used by HSG to track and describe stand volumes. Previous studies (Williams 1990b; Willcocks *et al.* 1990; Whitmore 1995) show that volume curve changes have a large impact upon the results of forest-level models. Therefore, accuracy in yield curves is important. One set of yield curves was developed for this study and used in all the simulations.

Plonski's (1981) yield curves were used as a base for the development of the pure-species yield curves. In all cases merchantable volumes were used. These curves were refined in two steps. Abitibi Consolidated has established permanent sample plots (PSP) for the jack pine working group on the SRF and the adjacent forest to the west, the Manitou forest. Approximately 300 PSP have been established since 1955 and remeasured each decade. This data set was made available and used to adjust Plonski's jack pine yield curves for local site conditions. The relative adjustment to the jack pine curves was then applied to the other species. Professional judgement, aided by a two-day field trip to the SRF, was used to further refine the yield curves (Gooding 1997).

3.4.2 Price and Product Value Curves

Price curves were developed for site classes based upon the expected product mix, piece size and cull. The curves were then expressed as age-dependant lookup tables (Gooding 1997).

3.4.3 Silviculture System Costs

Silviculture system costs were divided into the following sections:

1) Harvest Costs

For this study, harvest costs were the total costs accrued in producing wood products at roadside. A cost curve was developed to reflect the change in clearcut harvesting cost with piece size. This curve was subsequently used as a baseline and scaled upward by a factor of 1.5 for multiple entry harvesting and 1.3 for release harvesting (Gooding 1997).

2) Crown Charges

For this study, two Crown charges were included: the $1.50 charge on all hardwood species harvested and the $7.00 charge on all conifer species harvested. These charges apply to all harvested volume regardless of the silvicultural system used.

3) Regeneration Costs

The costs of each stand's regeneration treatment were calculated according to the method suggested by Moore *et al.* (1994).

3.4.4 Transportation Costs

Transportation costs are all those costs that can be expressed as a function of stand distance from the mill. HSG 3.0 permits new *transportation cost files* to be loaded during a simulation to account for additional road construction or abandonment. However, in this study only one fully developed road network was used and thus no primary or secondary road construction costs were assigned. Primary and secondary road maintenance costs were assigned as a component of transportation costs.

The amount of tertiary road constructed and maintained was a factor of stand area and not on the distance to a primary or secondary road. An average cost for tertiary road construction was included in the harvest cost.

In order to run the economic model, a transportation cost was required for each stand in the inventory. Transportation costs for each of the road classes (highway, primary, secondary and tertiary) were established (Gooding 1997). A transportation cost surface was then developed using the IDRISI COSTGROW module (Eastman 1992a; 1992b). High transportation costs were assigned to non-forest areas (i.e. water and bogs) to "force" the tertiary roads to follow land.

3.4.5 Output Modifications

The output files contain fields that describe the various biological attributes of the forest and the treatments applied. Three new fields were added to the HSG 3.0 summary files:

1) Delivered Wood Cost (C + M as defined in equation 1)
2) Transport Cost (M as defined in equation 1)
3) Residual Timber Value (RTV = P – (C + M) as defined in equation 1).

Residual Timber Value can be considered stumpage that could be collected by the landowner if the wood had been sold in a competitive market (Nautiyal 1988).

3.5 HYPOTHETICAL FOREST AGE CLASS STRUCTURES

Computer-generated hypothetical forests were constructed for two reasons. One was to test and debug model behavior using simple forest structures. The other reason was to test the hypothesis that forest age-class structure would have a large impact on the biological and economic indicators of a management strategy (Willcocks *et al.* 1990; Clarkson 1993; Whitmore 1995).

In generating the hypothetical forests, the existing polygon structure (7093 polygons) remained constant, but the fields for stand date of origin, site class, stand stocking, and species composition were altered for those records containing merchantable forest stands. The first step was to prepare a list of suitable species compositions representative of stands in northwestern Ontario's boreal forest (Gooding 1997). This species list was randomly assigned to stands using the random number generator in FoxPro 2.6 (Microsoft 1993). The range of site classes was reduced from five in the original SRF inventory to three, and forest stands were assigned randomly to a class. Stand stocking was changed to fully stocked (100%) for all stands to further simplify the forest structure.

Using this resulting forest structure as a constant base, three age-class structures (normal, young and old age) were prepared to test the impact of changing the initial age class structure. The normal forest was prepared by assigning ages between 1 and 100 to all forest stands randomly. The young forest was developed by assigning the same range of ages but the random number generated was squared to create an exponential distribution. The old forest was prepared by rerunning the young and subtracting the result from 100 (Figures 5,6 and 7).

3.6 MANAGEMENT STRATEGIES

The implications of applying alternative silvicultural systems to the SRF were explored through comparisons of results from computer-simulated management scenarios. The individual scenarios represented forest management strategies. These strategies, in turn, were derived from the two broad management philosophies of harvest exclusively by clearcut and harvest by alternative silvicultural systems.

Four forest management strategies were explored: 1) clearcut management; 2) constrained clearcut management 3) combined management; and 4) no-clearcut management. The permissible silvicultural treatments were matched to a set of silvicultural ground rules for each strategy. The silvicultural ground rules along with the management strategy goals were then used to develop specific scenarios. The maximum long-term sustained yield was determined for each management strategy scenario through a series of HSG runs that produced an even-flow of timber over a 200 year simulation period. The constrained clearcut strategy was differently as described below.

3.6.1 Clearcut Strategy

The clearcut strategy was included in this study as a benchmark of forest management activities widely practiced in northwestern Ontario's boreal forest over the last few decades. The aim of this management strategy was to harvest wood only by clearcutting and to regenerate harvested stands to an acceptable species stocking level at a free-to-grow status (OMNR 1986). No site conversions were permitted in this strategy. Conifer species were planted or seeded following site preparation on conifer forest types. Natural regeneration was used to regenerate deciduous forest types. There was no limit placed on the maximum level of artificial regeneration treatments.

3.6.2 Constrained Clearcut Strategy

The constrained clearcut strategy applied a clearcut strategy but the annual harvest level was constrained to match the long-term sustained yield (LTSY) harvest level achieved by the combined management strategy. This provided a comparison has of two strategies with equal harvest volumes.

3.6.3 Combined Strategy

The combined strategy harvests the maximum long-term sustained-yield from the forest by first harvesting wood volume with alternative silvicultural systems. The release harvest treatment is initially applied. If the harvest target has not been satisfied, the multiple entry harvest treatment is applied. If the harvest target is still not met, volume is harvested with clearcut silvicultural systems.

3.6.4 No-Clearcut Strategy

The no-clearcut strategy used alternative silvicultural systems and natural regeneration to obtain wood volume. This strategy represents an extreme application of alternative silvicultural systems in the boreal forest. It was included to examine the impact of a clearcut harvesting ban. The aim of this management strategy was to harvest wood without clearcutting while maintaining a suitable forest cover of merchantable species. Unlike the clearcut strategy, stand conversion between species composition was permitted.

Two alternative silvicultural treatments were developed for this strategy: a release treatment for spruce growing in young (40 to 60-year old) jack pine stands, and a "hold volume on the stump" treatment for mature stands. These two multiple entry harvesting treatments were chosen because they were felt to have practical application in northwestern Ontario's boreal forests.

The multiple entry harvest treatment for mature stands was applied to a stand at the point in time where it begins to lose volume and "break-up". At this point, gaps form in the canopy, an understory becomes established and the stand begins to convert to a new structure. The scenario used in this study assumes that 30% of the stand volume can be harvested by individual tree selection and the remaining stand will regenerate and fill in over time. This multiple entry harvest treatment would result in an uneven-aged stand comprised of a mixture of species and ages. Stands treated through this system were harvested every 30 years and the cycle was assumed to be sustainable for 200 years.

4.0 RESULTS

4.1 MODEL BEHAVIOR

4.1.1 Specific Examples Related to the Behavior of the Opportunity Cost of Harvest Delay (Rule_3)

A stand's price, harvest cost and residual value (excluding transportation cost) change as a stand develops. Understanding these relationships is crucial to understanding the operation of Rule_3. To demonstrate these relationships and the application in this study, a Sb_5 Pj_5 stand[3] which changes up into a Sb_8 Sw_1 at 130 years is used as an example (Figure 8).

The abrupt change in values between 120 and 130 years, is due to stand development and break-up. The economic operable range of the stand is defined by the economic operability minimum (i.e. in this study: the range of stand conditions where the RTV is positive). For example, if the transportation cost for this stand were $40.00 per hectare, the economic operable range would be in the stand ages of 68 to 123 years and greater than 173 years.

Stand development is reflected in the opportunity cost of harvest delay and stand volume (Figure 9). To be eligible for harvest, volume-based conditions must also be satisfied.

[3] The Sb_5 Pj_5 refers to a stand which is 50% black spruce and 50% jack pine. In the OMNR - FRI definition the 50% would be the species composition based upon crown closure, where the total for the stand must equal 100%. The format used in this thesis follows to the HSG format. The 5 refers to 50% stand composition and stand white spruce volume. This stand is only 90% stocked.

The operable volume range for this stand defined by the *OPMIN* command is between the ages of 40 to 130 years and then from 135 years onwards.

The abrupt loss of volume after 110 years is reflected in the spike in opportunity cost after 110 years. The opportunity cost is calculated using the average change in stand components over the next ten years. The main factor which determines opportunity cost is the rate of change in stand value which in turn is driven mainly by change in volume. In the example, a 120-year-old stand would be harvested first, then stands at 130 then 110 years of age, followed by other stands in decreasing order of opportunity cost (Figure 9).

The most apparent trend for opportunity cost is that it increases with stand age from 30 years (Figure 9). When opportunity cost is negative, the stand is growing in value at a rate greater than the interest cost to hold it, and should be left to grow. When the opportunity cost is positive, the cost to maintain the stand is greater than the increase in value so the stand should be harvested. The optimal economic rotation age is when opportunity cost equals 0 or approximately 70 years with no soil expectation value (SEV) and 65 years with SEV. SEV is a value that represents the value of bare forest land, from which an infinite series of harvests are expected (Pearse 1967). The biological efficient harvest age (age of maximum MAI) is 70 years, 5 years greater than the economic age of 65. Notice that the stand is still increasing in value (on a per cubic meter basis and in total volume) at age 70, but the opportunity cost of harvest delay is positive. According to strictly economic criteria, the stand should be harvested even though it is still increasing in value. The rate of increase in stand value is less than the interest cost to keep the stand. The opportunity cost rule behaves as predicted; young stands should not be harvested and as the stand grows older, the cost to maintain it increases. In addition, the economic harvest age is less than the biological rotation age (when the discount rate is not equal to 0).

Rule_3 harvests stands in decreasing order beginning with the highest opportunity cost. In this case the oldest stand would be harvested first. However, when more stands with different stand compositions are introduced the situation is more complicated. The economic harvest rule contains an optional feature where the user can define an operability range based upon the stand's RTV. For this stand, the RTV is positive for all ages above 30 years and negative for all those below (not shown in Figure 9). Setting a minimum RTV of 0, ensures that the rise in opportunity cost present at the young ages (which is due to zero values for some of the inputs) will not permit a stand to be considered for harvest before it is 30 years old.

The RTV has a large impact upon the opportunity cost of harvest delay. This can be demonstrated through changes in the transportation cost, which is one of the components affecting RTV. Figure 10 charts the opportunity cost of harvest delay with three different transportation costs. As the transportation cost increases (resulting in a lower RTV), the opportunity cost decreases. Therefore, stands with a lower RTV (profit) would be scheduled later while stands with a greater RTV would be harvested at a younger age on a shorter harvest rotation. This result is consistent with economic theory (Pearse 1967; Nautiyal 1988).

4.2 EFFECTS OF INITIAL FOREST AGE-CLASS STRUCTURE ON TIMBER SUPPLY

The three management strategies - clearcut, combined and no-clearcut - were run with each of the three hypothetical forest inventories. For each strategy, the percent change in the LTSY from the normal forest's LTSY was determined (Table 1 and Figure 11).

The results show that the effects of changing age-class distributions upon the LTSY were not consistent. For the younger forest initial conditions, all three strategies resulted in a reduction in the LTSY compared to the normal forest. The no-clearcut strategy produced the greatest reduction in LTSY due to the specific stand structures required for harvest.

When the initial forest is older than normal, the impact on LTSY among the three strategy scenarios varied (Figure 11). The LTSY from the no-clearcut scenario increased while that from the combined scenario decreased. The clearcut scenario displayed only a slight (2%) increase in LTSY. The increase in the no-clearcut scenario's LTSY is due to the older stand structures required for harvest eligibility. The decrease in LTSY associated with the combined scenario was unexpected considering that this scenario is a combination of the other two scenarios, both of which had increased LTSYs. This result is likely explained by the larger number of stands that were tied up in the multiple entry harvest treatment for the older forest. The multiple entry harvest treatment was applied before clearcutting, and an older forest would have had more eligible older stands. The remaining stands that were clearcut were insufficient in number to raise the harvest volume above that achieved for the normal forest. The combined result is a lower LTSY for the older forest.

4.3 EFFECTS OF MANAGEMENT STRATEGIES

4.3.1 Effects of Management Strategies on Timber Supply

The clearcut strategy produced the highest LTSY (Table 2). A 24% reduction in the supply occurred when the combined strategy was applied. An even greater reduction (65%) occurred with the no-clearcut strategy. This result supports what most foresters have traditionally believed; that in the Boreal forest, maximum volumes are obtained from even-age management.

On an annual basis, clearcut management disturbs less area than either the no-clearcut or combined strategies (Table 2). The difference in area disturbed is even more pronounced when the volume produced by each hectare harvested (harvest yield) is considered. The clearcut is far more productive; the volume of timber recovered per hectare is 2.2 times that of combined management (136 vs. 64 m^3/ha) and 3.7 times that of the no-clearcut strategy (136 vs. 37 m^3/ha).

The harvest becomes more productive in terms of volume harvested per hectare (Table 2) under the constrained clearcut strategy. Harvest area decreases 35% from 2,300 to 1,500 ha/year, and recovered volume increased from 136 to 159 m^3/ha. This increase in yield was due to the greater volume present in the stands harvested by the constrained clearcut strategy.

When compared to the combined strategy, the constrained clearcut strategy required only 41% (1,500 vs. 3,700 ha/year) of the total area to produce the same yield. Clearcut management is perceived by many to have a greater detrimental impact upon the forest. However, since the clearcut strategy required only 41% of the annual harvest area compared to the combined strategy, one might well question which management alternative actually has greater impacts upon the forest.

4.3.2 Effects of Management Strategies on Forest Age Class Structure

The results (Table 2) clearly favour clearcut management. However, producing higher levels of fibre at the expense of desirable forest conditions may not be acceptable. This raises the question of what future forest structures is achieved by each of these strategies. One measurement of forest structure is age-class distribution (Figures 12, 13, 14, 15)

Clearcut management (Figure 12) altered the forest structure from an initial medium/old-aged forest with an uneven age-class distribution to a young "regulated" forest by 2055. Constrained clearcut management (Figure 13) produced a more balanced age-class distribution. It produced a wider range of ages than any other management strategy. Combined management (Figure 14) produced a future forest age-class structure that is between that of clearcut (Figure 12) and no-clearcut management (Figure 15). Combined management did not change the initial forest structure as abruptly, nor to the same extent as the other two management strategies. Under no clearcut management the amount of area in the older age classes continually increased. After 60 years, there is little area less than 60 years of age in the forest (Figure 12).

The comparison between the age-class distributions of the combined and the constrained clearcut scenarios is useful because both produce the same volume of timber. The constrained clearcut scenario has an age-class distribution which is more evenly distributed than that of the combined management scenario. This result was somewhat unexpected given that a combined management strategy is widely perceived to produce forest structures that are environmentally friendly. The combined strategy kept stands within a narrow age range while repeated multiple entry treatments were applied.

4.4 THE COMBINED EFFECTS OF INITIAL AGE CLASS STRUCTURE AND MANAGEMENT STRATEGIES ON ECONOMIC INDICATORS

The hypothetical forests were used to determine the economic effects of different age-class distributions. The RTV's for each age-class under the different strategies are displayed in Table 3, along with the percentage change from the normal age-class.

The direction of change in RTV's is consistent for all strategies, increasing as age increases (Figure 16). However, the amplitude of change is not consistent across the strategies. Profits under the combined strategy are the most sensitive to age structure.

An analysis of the effects of the four management strategies on economic indicators ($/m^3) is useful to pinpoint how the strategies differ in terms of costs (Table 4). Immediately apparent is the small amount spent on regeneration in comparison to other costs. This indicates that although no-clearcut management achieves a drastically lower regeneration cost, this benefit is easily offset by minimal increases in harvest costs. This result would appear to falsify the theory that alternative management silvicultural systems significantly reduce total costs by decreasing regeneration costs.

The minimal variation in costs across the strategies in comparison to the variation in RTV demonstrates the danger of using only cost in an analysis of this sort: the combined impact of price and cost may be more important than either one alone. The importance of price is further illustrated by the trajectories of economic results over the simulation period of 200 years (Figures 17 and 18). The wood costs are delivered wood costs and are consistent during the simulation. Since RTV is price less delivered wood cost, the deviations between delivered wood cost and RTV are due to fluctuations in price. Therefore, the variation observed in RTV values in Table 2 is due to variations in price associated with stands in the harvest profile.

4.5 EFFECTS OF HARVEST LEVELS ON ECONOMIC INDICATORS

A comparison of the RTV's produced by no-clearcut and clearcut management (Table 4) appears to favor no-clearcut management (26.30 $/m^3 vs. 13.41 $/m^3). However, when the clearcut strategy is constrained, it produces the highest RTV (27.84 $/m^3). This illustrates the large impact that harvest levels have on RTV's and therefore on economic performance.

Expressing the economic indicators in terms of total dollars (Table 5) further captures the impact of harvest levels. The constrained clearcut strategy can now clearly be seen to be the most profitable option, producing a total RTV of $6.5 million/year as compared to $4.2 million/year under the unconstrained clearcut strategy. The apparently similar benefits that the no-clearcut strategy achieved at the $/m^3 level disappear when the total value is considered. In fact, this strategy results in the lowest RTV.

Comparison of the two clearcut strategies indicate the following relationship: as LTSY decreases, RTV increases. This is due to the harvest costs of marginal stands being greater than the revenues that they generate. The marginal cost (cost of the last unit of output; Nautiyal 1988) is greater than the marginal revenue (revenue of the last unit of output) resulting in decreased return per dollar invested as LTSY increases. Therefore, harvesting at the maximum LTSY does not maximize profit. This relationship is demonstrated for clearcut and combined management (Figure 19). The same total RTV can be obtained for clearcut management by reducing harvest levels by half. Similarly for combined management, the same RTV can be obtained with a 25% reduction in harvest levels. These results suggest an interesting dilemma for publicly held land such as the SRF.

The trajectories of RTV over time for the clearcut, constrained clearcut and combined strategies further exhibits the high economic performance of the constrained clearcut strategy (Figure 20). Another benefit of this strategy is also exposed. All three strategies experience a drop in profitability after 50 years due to the reduction in the availability of "high quality" stands. However, the constrained clearcut strategy maintains a more consistent RTV and recovers to the original RTV at a faster rate. This characteristic facilitates long-term economic stability.

4.6 COMPARISON OF VOLUME AND ECONOMIC-BASED HARVEST SCHEDULING RULES

Simulation results from economic scheduling were compared to results from volume-based harvest scheduling. Both harvest scheduling rules produced the same general trends regarding LTSY for each management strategy (Figure 21).

The different harvest rules generated harvests with distinctive economic indicators. All three scenarios run with volume-based harvest rules produced negative RTV's (Table 6). The main reason for these negative RTV's is the large transportation cost associated with the volume-based harvest scheduling strategies.

The friction surface used to generate the transportation cost placed large costs on water crossings. This produced a transportation cost structure that contained a few stands with transportation costs in excess of $1000/m^3. These are extreme costs, but they serve to demonstrate what happens when no economic bounds are put on harvest areas. The stands with the extreme transportation cost were not harvested by the economic harvest rules.

In summary, economic harvest scheduling produced greater overall economic efficiency compared to volume-based rules. This suggests that the current use of volume-based rules in Canada should be carefully reviewed.

5.0 DISCUSSION

5.1 MODEL BEHAVIOR

The modeling process is progressive in that observations of current model performance leads to suggestions for improved future models. The following are recommendations generated from the experiences acquired in this study.

The scenarios used in this study assumed that all of the forest area was available for timber harvesting without any restrictions. This is an unrealistic assumption. In Ontario, guidelines and regulations place restrictions upon timber harvesting and regeneration activities to protect wildlife and other forest values (OMNR 1995). Harvesting restrictions applied to the scenarios used in this study would be expected to reduce the sustainable harvest levels from strategies employing clearcutting to a greater extent than those employing alternative silvicultural systems. Additional research in this area could be undertaken through the use of HSG 3.0's adjacency constraint and green-up delay function and rerunning the scenarios. The method used in this study applied temporal constraints to harvesting which reduced the LTSY under the no-clearcut and combined strategies. Combined spatial and temporal constraints will likely have a significant and negative impact on LTSY. Many projections of LTSY have not yet fully accounted for these constraints in Ontario.

The traditional yield curve format used in forest-level models does not work well with the alternative silvicultural systems used in this study. For forest level analysis, silvicultural treatments that manipulate stand structure require yield curves to reflect this manipulation. The problem is that stand response can be vastly different for each treatment type, stand type and entry age. This could result in thousands of possible treatment combinations and yield curves. The data set thus becomes too large to comprehend. One solution to the limitations of yield curves to model stand growth is to replace them with stand models. This is the approach used in the Landscape Management System (LMS) (McCarter 1995). The biggest problem of applying a similar technique in Ontario's boreal forest is the lack of calibrated stand (or tree) growth models to replace yield curves.

A detailed sensitivity analysis was not conducted on the data set used in this study. Sensitivity analysis could have been conducted by changing one component at a time such as the volume yield curves. This would have provided insight into the growth assumptions used. Changing the economic yield curves would have provided insight into the sensitivity of product prices and harvesting costs. Different road structures could have been used to determine the impact of potential road networks. Other factors such as changes in the discount rate or the definition of sustainability could have been tested.

Caution must be exercised when applying these results to other forests or conditions - they are not directly transferable. Other forests could be examined for the economic impacts of various forest management strategies by applying a range alternative of silvicultural systems and using methods similar to those developed for this study. Sensitivity analysis will be an essential element of these applications.

5.2 EFFECTS OF FOREST AGE-CLASS STRUCTURE

The results support the conclusion that initial forest structure is a significant short-term factor in forest projections (Whitmore 1995). The direction of alternative silvicultural system's impact upon sustainable harvest levels was consistent between the SRF and the hypothetical forests. However, the impact of changing age-class structure upon sustainable harvest levels was not consistent. Establishing a normal forest as a base, the younger forest resulted in a reduction of sustainable harvest levels from 7% to 30% while the older forest resulted in a reduction for the combined strategy of 14%. By comparison, the clearcut and no-clearcut strategies increased sustainable harvest levels by 2% and 12% respectively. These results are counterintuitive, thus confirming that forest-level models are critical analysis tools in the planning process. Only through a program of rigorous testing of management alternatives can the potential long-term forest-level implications be determined.

The study's results suggest that future forest structure is affected more by harvest level than by the silvicultural system employed. It was expected that the combined management strategy would produce the greatest diversity of forest structure. However, from the response variables used in this study, both the constrained clearcut strategy and the combined management strategy resulted in comparable forest age-class structures. More research should be conducted in this area of assessing the biological consequences of different forest level patterns arising from competing management strategies. Indeed the field of landscape ecology is devoted to this pursuit (e.g. Turner 1989).

5.3 EFFECTS OF MANAGEMENT STRATEGIES

Foresters have traditionally supported the concept that maximum yield is produced in the boreal forest from even-aged management (Smith 1986; Davis and Johnson 1987). In the boreal forest, foresters have assumed that alternative silvicultural systems will produce a lower yield from regeneration lag, inferior stocking, reduced growth from shading and the establishment of lower-yield species (Smith 1986; Davis and Johnson 1987; Koven and Martel 1994). This assumption has never been tested in a rigorous manner in Ontario.

Studies in other locations have suggested alternative silvicultural systems may be more efficient at produced timber yields compared to clearcutting under some conditions (Wykoff *et al.* 1982; Haight and Monserud 1990). However, when natural regeneration is encouraged in a shelterwood or multiple entry harvest system on many sites in northwestern Ontario, a mixture of balsam fir and white and black spruce will develop. These species compositions will increase the chance of spruce budworm infestations resulting in yield losses and mortality. This concern is strong enough that some management plans in northwestern Ontario (e.g., Canadian Pacific Forest Products 1991) call for a reduction in the balsam fir component through an aggressive stand conversion program. This raises skepticism of the utility of alternative silvicultural systems in the boreal forests of Ontario.

Some of the professed stand-level benefits of using alternative silvicultural systems, such as reduced harvesting impacts (thus providing better integration with other forest users) have been assumed to apply at the forest level. The results in this study display that quite the opposite result is possible. When clearcutting is replaced with alternative silvicultural systems, nearly twice the forest area must be operated annually to produce the equivalent wood volume. Alternative silvicultural systems spread the harvest activity across the forest landscape, increasing the annually affected area and thus the impacts of logging upon the forest. This may make integration with other uses more difficult rather than easier. Forest managers must balance the public desire for alternative silvicultural systems with their negative impacts. In practice, it has been difficult to determine this balance because of the lack of data and practical tools to analyze the problem. The modified model developed for this study provides forest managers with a powerful tool for forest management planning.

The yield assumptions used in this study reflect the belief that alternative silvicultural systems used as a replacement for clearcutting systems in northwestern Ontario's boreal forest are, overall, less biologically efficient at the stand level. The study found that the stand-level reductions in yield (due to lower densities and older harvest ages) are amplified at the forest level. This trend is ultimately attributable to alternative silvicultural system's inflexible harvest scheduling. Overtime, managed stands should provide more flexibility in the application of alternative silvicultural systems than the natural stands present in this study.

Clearly the underlying assumptions of stand-level behavior require full verification and testing. To quantify stand-level behavior, the Canadian Forest Service initiated a multi-disciplinary study exploring responses to alternative silvicultural systems in the Black Sturgeon forest northeast of Thunder Bay (J. B. Scarratt pers. comm. 1994). Results from these studies could be easily incorporated into forest-level analysis using the methods developed and tested in this study.

These results contrast with those obtained by Haight (1987), Haight and Monserud (1990) and Yang and Bella (1994). Their studies showed positive returns for alternative silvicultural systems. The contrast may be explained by the different forests used in each study. The stand-level biological and economically efficient treatments applied in these other studies may well be inapplicable to northwestern Ontario boreal forests. More studies of stand-level responses to alternative silvicultural systems are required for a satisfactory explanation.

5.4 THE EFFECTS OF MANAGEMENT STRATEGIES ON ECONOMIC INDICATORS

One of the reasons Haight and Monserud (1990) achieved economic gains is the reduction in forest management costs through a reduction in regeneration costs. This reduction in regeneration costs and perceived benefits of "natural regeneration" contributed to the Ontario Ministry of Natural Resources' (OMNR) decision to increase the use of alternative silvicultural systems (OMNR 1993b; Koven and Martel 1994). However, this study has indicated that lower regeneration costs are not sufficient to offset the increased harvesting and delivery costs.

Banning clearcut harvesting in the boreal forest could have serious economic ramifications. The consequences of a reduction in the sustainable harvest levels and the residual timber value that accrues to the timber company may result in a reduction in the number of timber-based facilities and related jobs. Even with these harvest level reductions, industrial forest operations would continue to require the whole pre-reduction forest landbase. The degree to which the dispersal of industrial harvesting activities would affect the tourism industry was not considered in this study and requires further research.

No comparable forest-level economic studies of alternative silvicultural systems in the boreal forest could be found. However, the OMNR recently conducted a study comparing clearcut strip harvest with natural regeneration and traditional clearcut and regeneration strategies on a boreal forest north of Thunder Bay (OMNR 1992). The results from the OMNR study support the findings produced here. The OMNR concluded that when alternative silvicultural systems are applied at the forest level, wood costs increase and allowable harvest levels drop.

5.5 EFFECTS OF HARVEST LEVELS ON ECONOMIC INDICATORS

The results of this study show that harvesting at the maximum LTSY does not optimize economic performance. Rather, profits are maximized at a harvest level below the highest LTSY. Economic theory tells us that this point is where marginal cost equals marginal revenue, or where the cost of harvesting a tree is equal to its value. Therefore, it is in the landowners best interest to reduce harvest levels below the biological maximum to the economically optimum level. The need to find this level points towards the benefits of using economic rather than volume-based rules when setting harvest levels.

However, a decrease in harvest levels would have other consequences. Communities in the Boreal forest are highly dependent upon the continuous production of wood products (Beck *et al.* 1988, Nautiyal 1988). More research into the socio-economic costs of changing sustainable harvest levels should be considered.

5.6 COMPARISON OF VOLUME AND ECONOMIC-BASED HARVEST SCHEDULING RULES

Traditionally, and to the present day, forest managers in Ontario use volume-based rules to schedule stands for harvest. This method appears to be economically inefficient based upon this study's findings. The results also suggest that the allowable cuts estimated are probably too high for current wood value markets. In the boreal forest, economic wood supply can be significantly lower than the biological capacity of the forest to produce timber.

Economic harvest rules (e.g. Rule_3) produce not only greater overall economic efficiency, but also smaller economic fluctuations between periods. The economic costs to harvest at the higher levels produced by volume-based harvest rules may not be worth the additional volume gained. The results produced here support traditional economic theory and economic studies (e.g. Williams 1990a) that describe an appropriate harvest level as a function of price and delivered wood costs rather than as a function of LTSY.

Results of this study question the concept of a unique sustainable harvest level and challenges the validity of an optimum level of harvest. A model-derived optimum can be calculated but the quality of data and assumptions regarding various constraints make a model-derived optimum suspect. One solution is to consider more than one response variable when establishing timber harvest levels (e.g. harvested timber volume, residual growing stock, future forest structure, RTV, delivered wood cost). However, as more information is considered in the planning process, the sustainable harvest level becomes more difficult to define. This lack of a definitive sustainable harvest level supports a negotiated solution. A negotiated solution would undoubtedly highlight attention upon the forest management goals and assumptions. It would also reinforce the correct application of computer models in forest management; as decision support tools rather than the providers of the solution.

6.0 CONCLUSIONS

Modern forestry is increasingly replacing traditional clearcut silvicultural systems with alternative silvicultural systems. This trend is largely due to society's negative perception of the ecological and economic costs of clearcutting. However, the results from this study urge forest managers to follow a cautious approach when considering alternative silvicultural systems.

The optimal forest management strategy for a site cannot be identified until the ramifications of the available strategies can be predicted. Computer simulation of the various management options suggested that the switch to alternative systems in Canada's boreal forest would have negative economic and ecological consequences. The production of consumptive goods (timber) would decrease which could have serious socio-economic implications due to northwestern Ontario's forestry dependent economy. Non-consumptive goods and services such as recreational use and forest structure would also depreciate. Less intensive management techniques utilized in alternative systems would disperse forestry over a greater distance, resulting in more widespread environmental impact and reduced opportunities for alternative uses. The results also suggest that alternative management would result in a forest structure with a more uneven distribution of age classes. In addition, the perceived savings achieved from decreased regeneration costs were found to be minimal and were eliminated by the increased harvest and transportation costs.

On sites like the Seine River Forest, intensive management with clearcutting, planting, and thinning activities will likely be required on significant portions of the estate to maintain timber harvests at the current level. This is particularly true if other parts of the forest are allowed to develop to serve other purposes. The results of this study supports the idea of a triad of intensively managed forest, forest managed in a natural state, and protected forest as part of a rational ecosystem management strategy covering large geographic areas (Seymour and Hunter 1992).

Also of note are the results regarding optimum harvest levels. Current harvest levels determined by volume-based harvest scheduling are likely excessive from an economic point of view, due to the high cost of harvesting marginal stands. The cost of harvesting marginal stands is greater than their market value, resulting in reduced profits. The reduction of harvest levels is required to achieve economic efficiency. Therefore, the replacement of volume-based with economic-based harvest scheduling is recommended.

The results of this study suggest that the government, as landowner, must trade off the social and economic advantages associated with high LTSY against bequesting a lower forest value and associated “land rent” over the long run. In addition, cutting at the LTSY level may be economically inefficient in the short run.

Figures, Tables and Equations

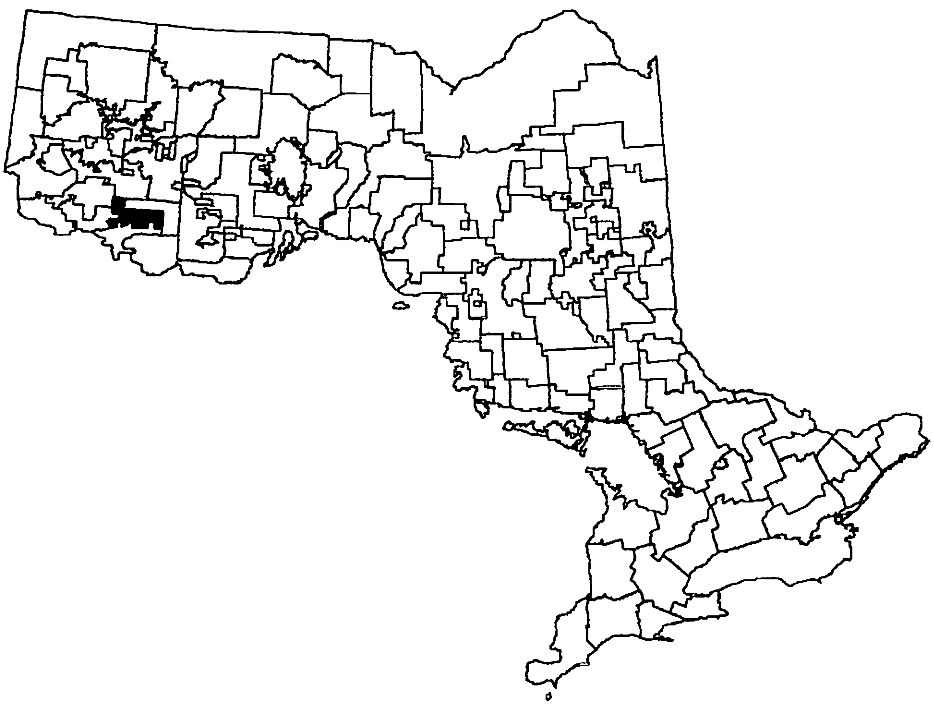

Figure 1: The location of the Seine River Forest and Forest Management Units in Ontario.

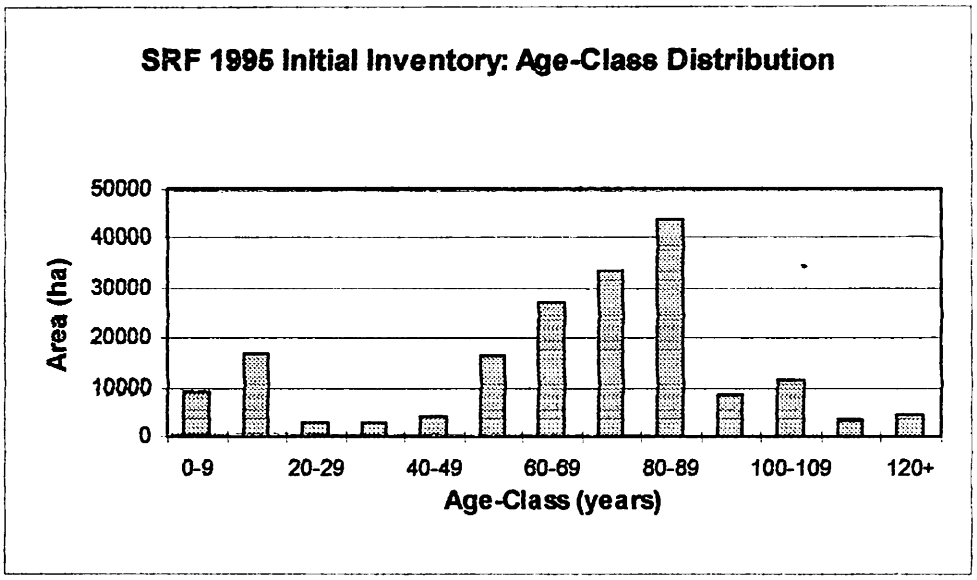

Figure 2. Ten-year age-class distributions of the initial SRF inventory advanced to 1995 as used for the HSG simulations.

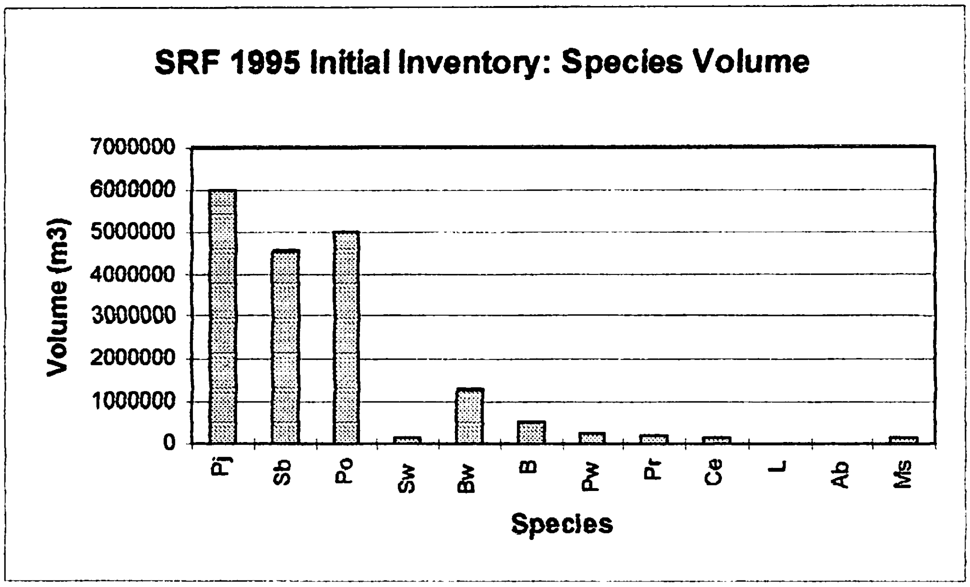

Figure 3. Total merchantable growing stock volumes of the species present in the SRF initial inventory advanced to 1995 as modified for the HSG simulations[4].

[4] Species follow OMNR FRI naming convention: jack pine (Pj), black spruce (Sb), trembling aspen (Po), white spruce ((Sw) *Picea glauca* (Moench) Voss), white birch (Bw), balsam fir ((B) *Abies balsamea* (L.) Mill.), white pine ((Pw) *Pinus strobus* L.), red pine ((Pr) *Pinus resinosa* Alt.), white cedar ((Ce) *Thuja occidentalis* L.), larch ((L) *Larix laricina* (Du Roi) K. Koch), black ash ((Ab) *Fraxinus nigra* Marsh.), soft maple((Ms) *Acer rubrum* L.).

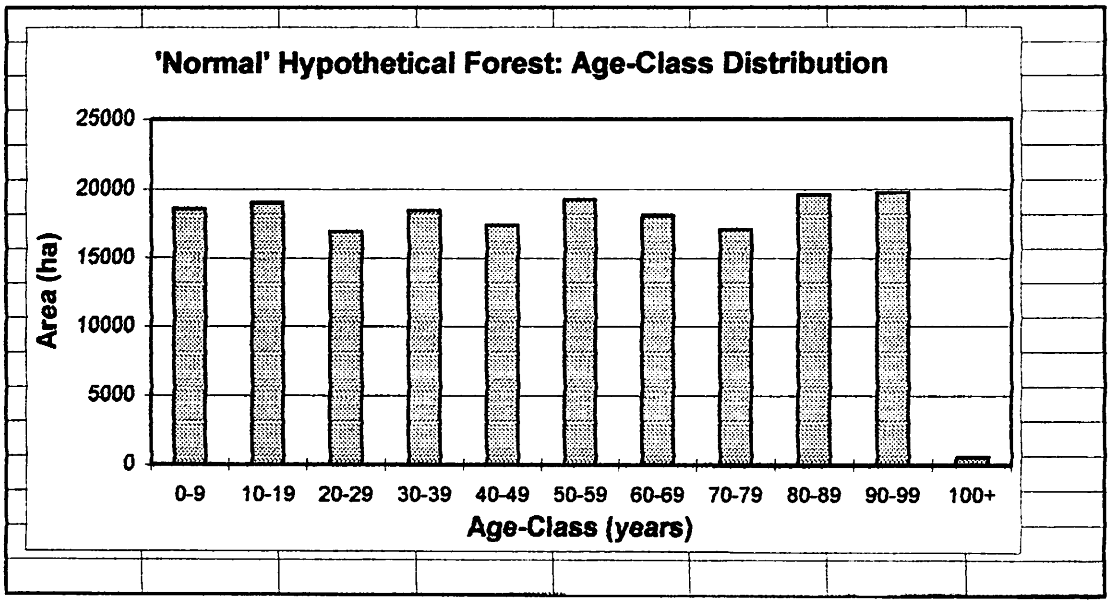

Figure 5. Ten-year age-class distributions of productive forest area updated to 1995 for the "Normal" hypothetical forest.

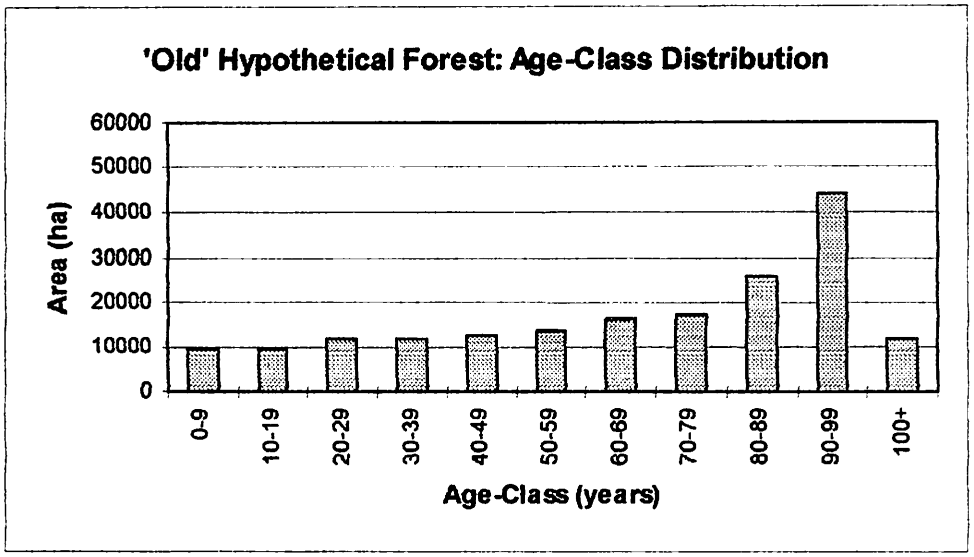

Figure 6. Ten-year age-class distributions of productive forest area updated to 1995 for the “Old” hypothetical forest.

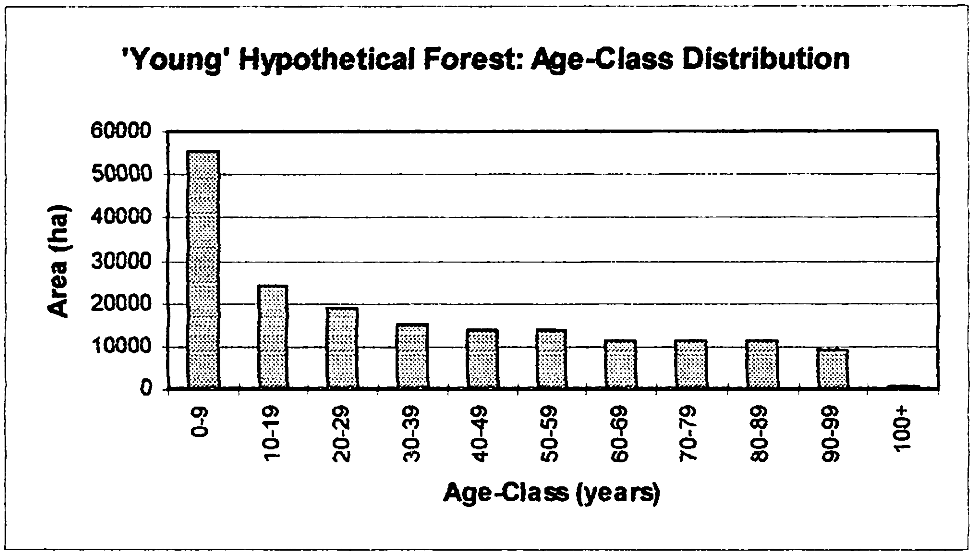

Figure 7. Ten-year age-class distributions of productive forest area updated to 1995 for the "Young" hypothetical forest.

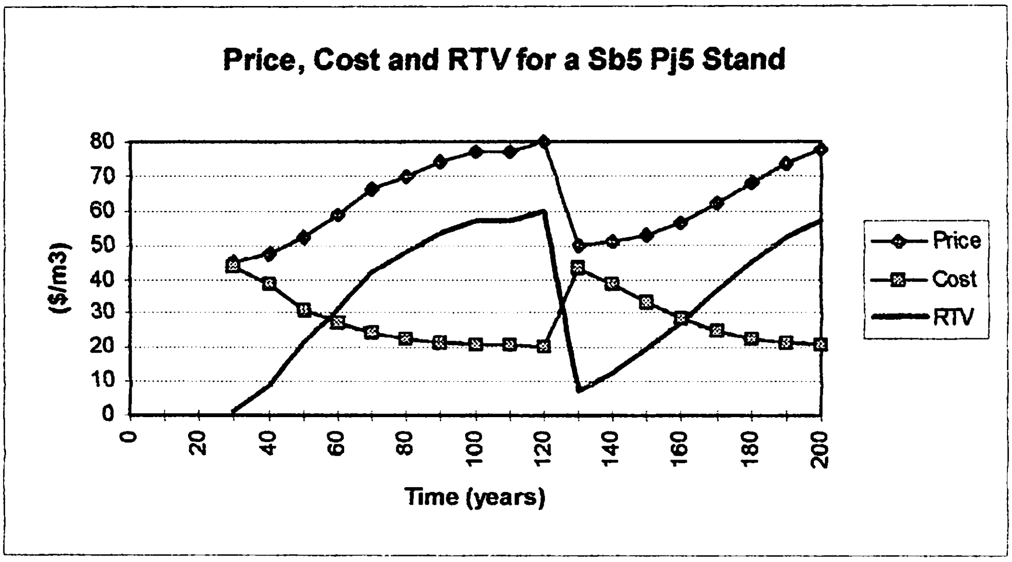

Figure 8. Price, cost and RTV (price - cost) for a Sb_5 Pj_5 stand which changes into a Sb_8 Sw_1 stand at 130 years.

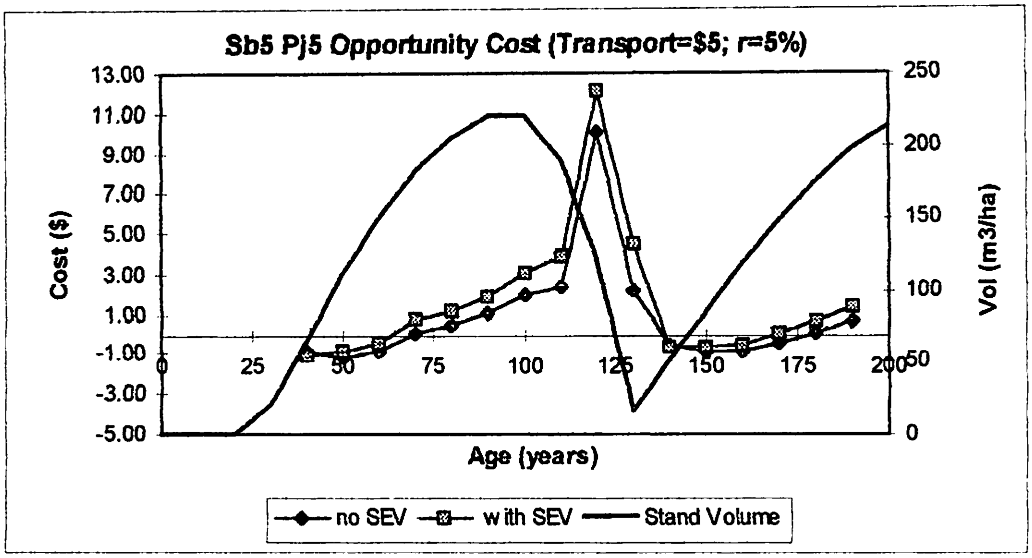

Figure 9. The opportunity cost of harvest delay calculated both with and without SEV for a site-class-1 Sb_5 Pj_5 stand with a transportation cost of $5/m^3$. The results are based upon the data used for the SRF and contain the break-up at 130 years to a Sb_8 Sw_1 stand.

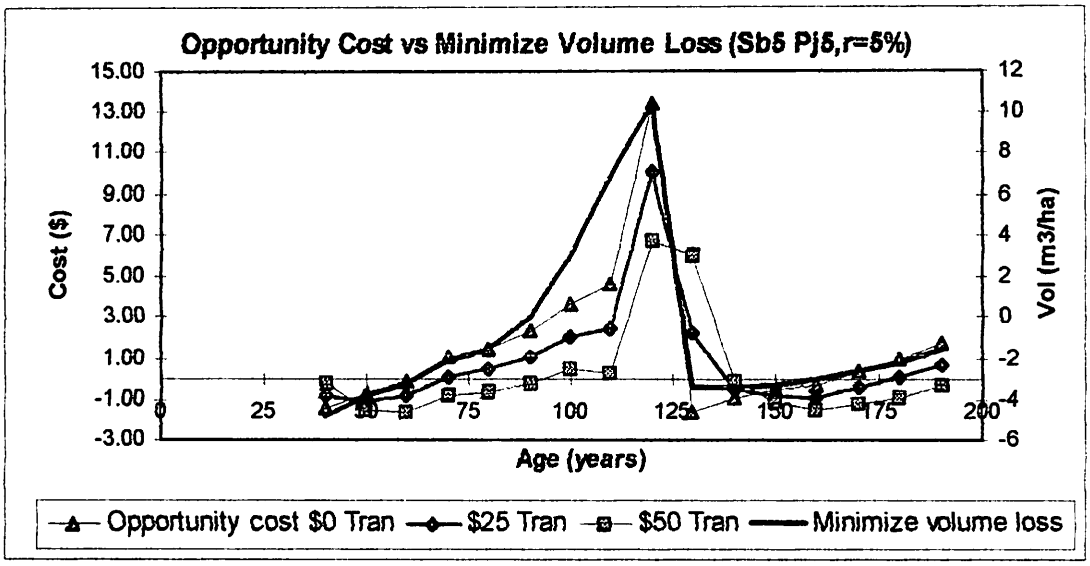

Figure 10. Comparison of opportunity cost of harvest delay priority rule (Rule_3) for three different transportation cost levels and the minimize volume loss harvest priority rule (Rule_2) for a site-class-1 Sb_5 Pj_5 stand undergoing break-up at 130 years to a Sb_8 Sw_1 stand.

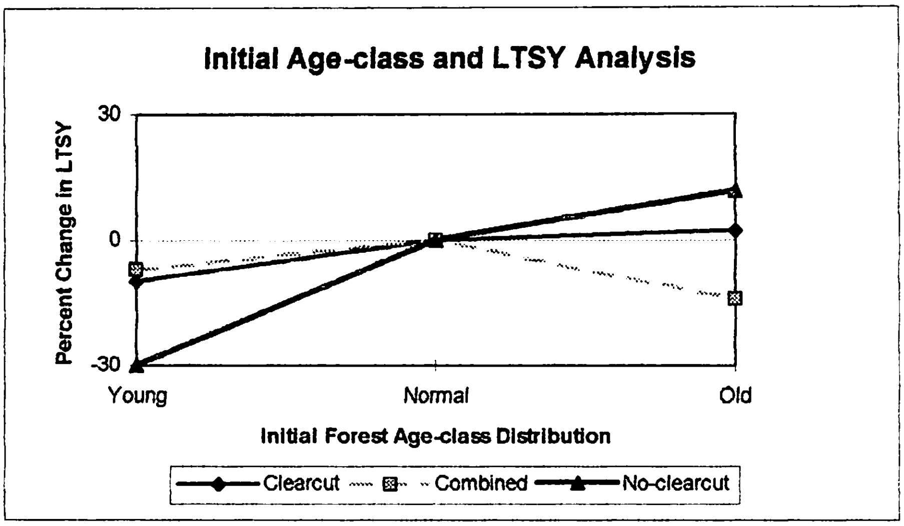

Figure 11. The percent change in LTSY resulting from different initial forest age-class distributions for the three management strategies; clearcut, combined and no-clearcut management.

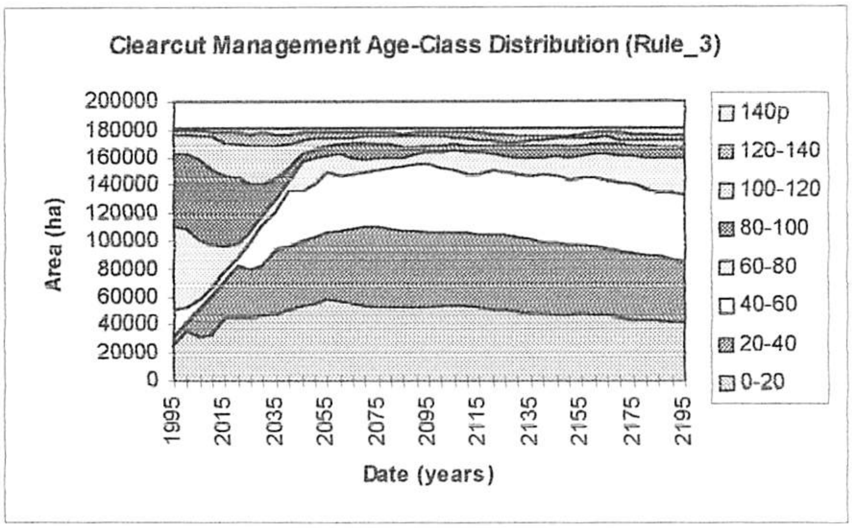

Figure 12. Predicted age-class distributions (ha) of the SRF forest resulting from clearcut management (310,000 m^3/yr) using economic-based harvest rules (Rule_3).

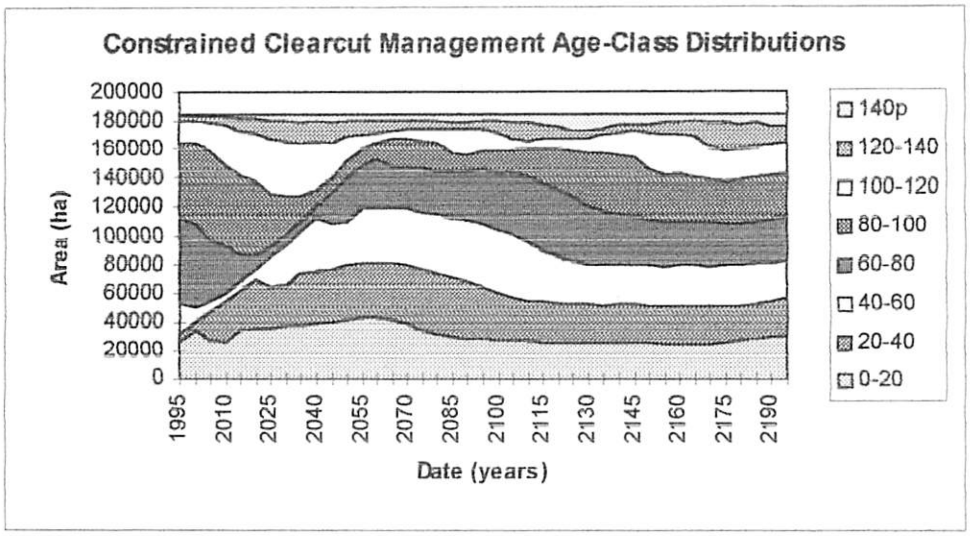

Figure 13. Predicted five-year age-class area distributions of the SRF forest resulting from constrained clearcut management (235,000m^3/yr) using economic-based harvest rules (Rule_3).

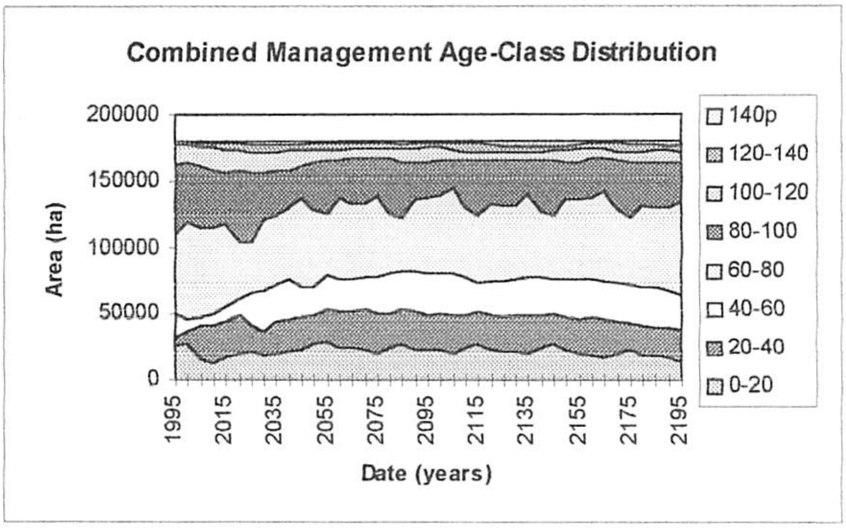

Figure 14. Predicted age-class distributions (ha) of the SRF forest from combined management (235,000 m^3/yr) using economic-based harvest rules (Rule_3).

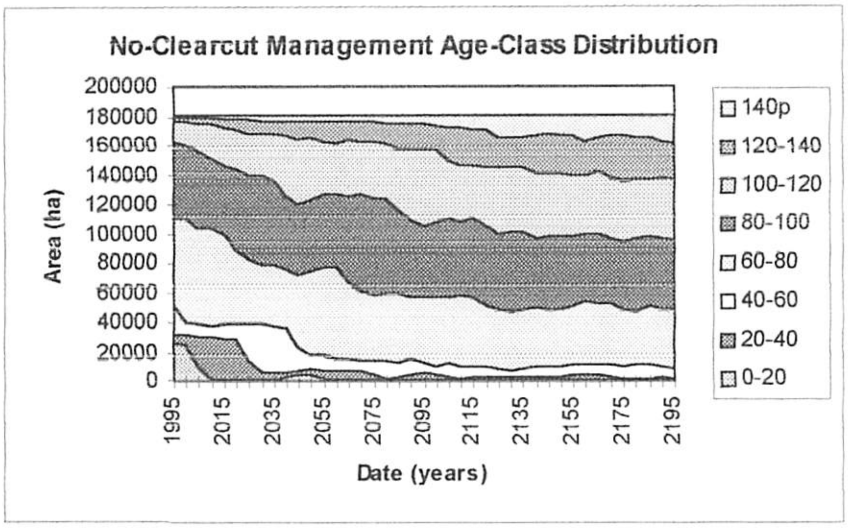

Figure 15. Predicted age-class distributions (ha) of the SRF forest resulting from no clearcut management (115,000 m^3/yr) using economic-based harvest rules (Rule_3).

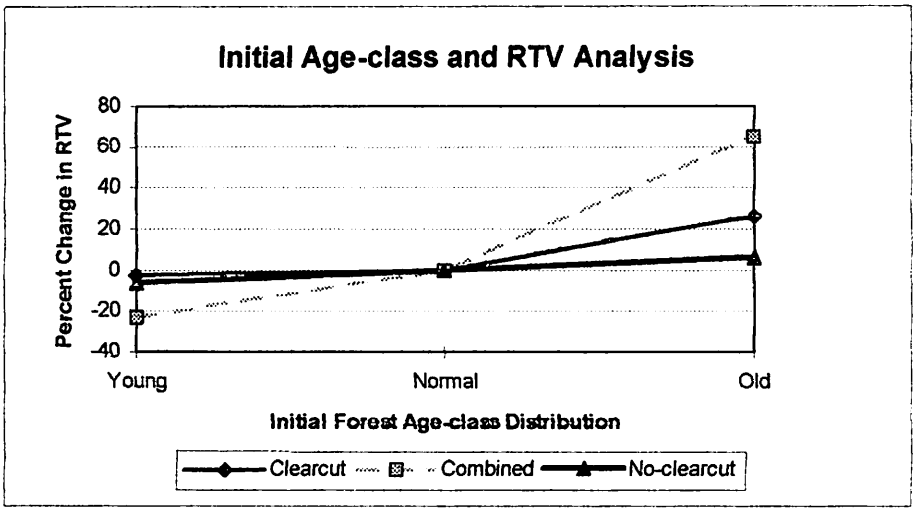

Figure 16. The percent change in RTV from the normal forest for young and old forest age-class distributions and the three management strategies.

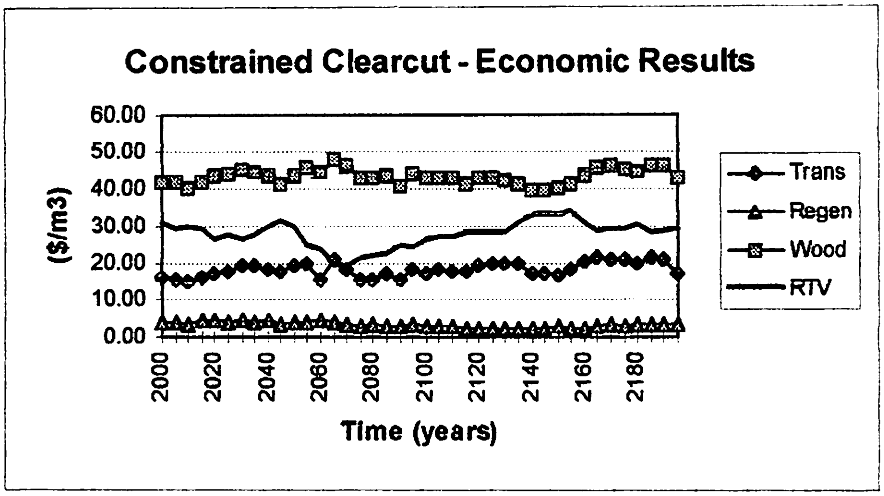

Figure 17. SRF predicted economic results (transportation cost, regeneration cost, delivered wood cost and RTV), for the clearcut management scenario constrained to 235,000 m^3/yr using economic harvest scheduling (Rule_3).

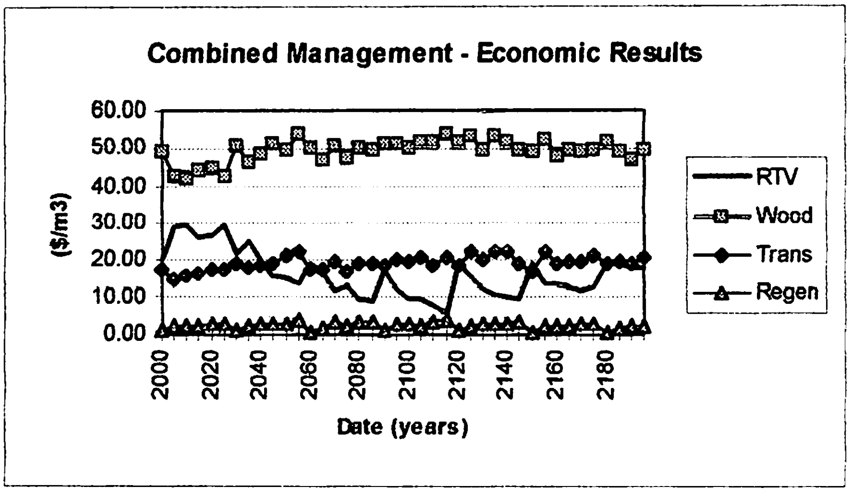

Figure 18. SRF predicted economic results (transportation cost, regeneration cost, delivered wood cost and RTV), for the combined management scenario at 235,000 m^3/yr using economic harvest scheduling (Rule_3).

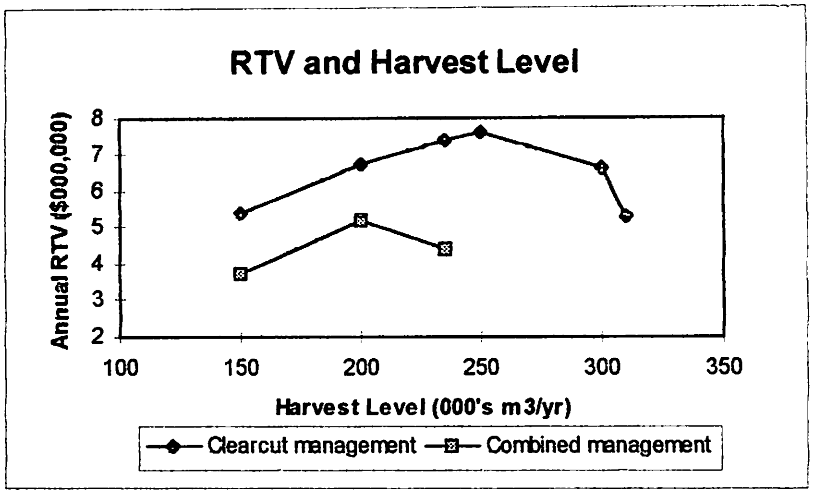

Figure 19. RTV's from different harvest levels for clearcut and combined management on the SRF. Harvest levels are expressed in thousands of m^3/year and RTV as 200-year average annual in $millions.

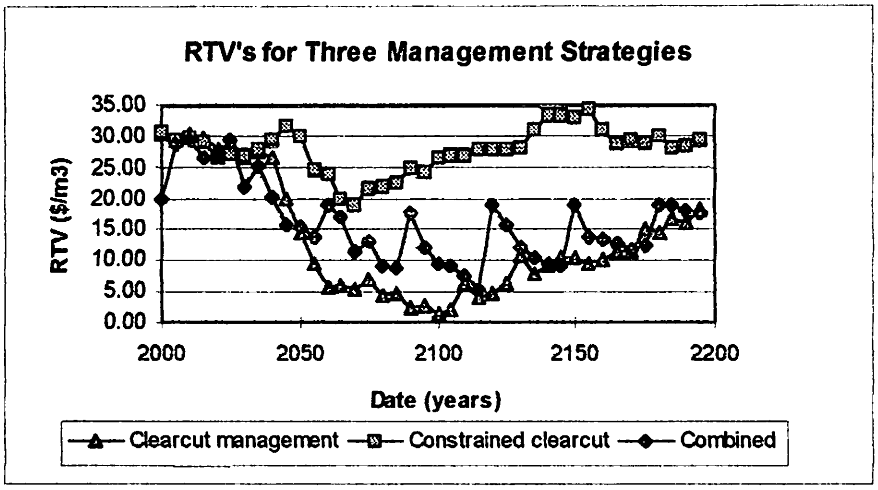

Figure 20. 200-year RTV's for clearcut, constrained clearcut and combined management strategies for the SRF.

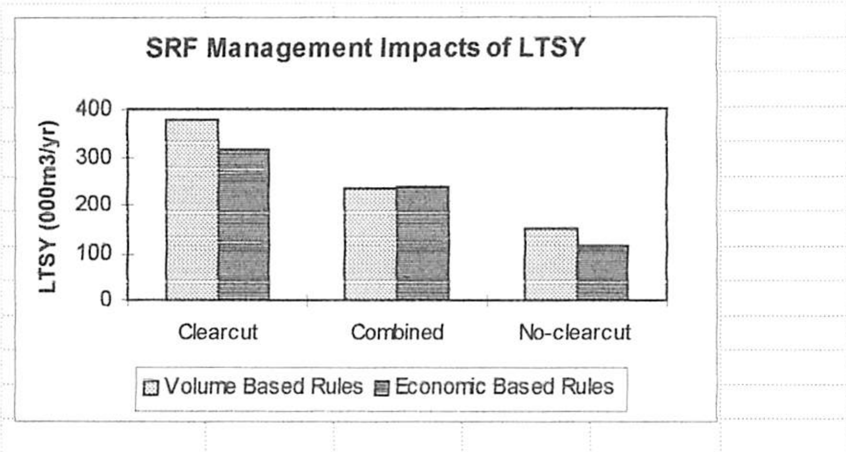

Figure 21. SRF 200-year LTSY produced by volume-based and economic-based harvest rules, for clearcut, combined and no-clearcut management strategies.

	Clearcut management		Combined management		No-clearcut management	
Forest	**LTSY** (000 m3/yr)	% Change	**LTSY** (000 m3/yr)	% Change	**LTSY** (000 m3/yr)	% Change
Young	306	-10	277	-7	60	-30
Normal	341	0	297	0	85	0
Old	346	2	257	-14	95	12

Table 1. LTSY (000's m^3/yr) of three different age-class distributions for the clearcut, combined and no-clearcut management scenarios.

SRF Harvest Scenario	LTSY (000 m^3/yr)	Harvest Area (ha/yr.)	Harvest Yield (m^3/ha)	Forest Yield (m^3/ha/yr)
Economic Harvest Rules				
Clearcut management	310	2,300	136	1.7
Clearcut (constrained)	235	1,500	159	1.3
Combined management	235	3,700	64	1.3
No-clearcut management	115	3,100	37	0.6

Table 2. Predicted 200 year average results for the SRF comparing annual target maximum long-term sustained yield (LTSY); annual harvest area; harvest volume divided by harvest area; and annual harvest volume divided by total SRF productive forest land base (184,427 ha).

	Clearcut Management		Combined Management		No-clearcut Management	
Forest	**RTV** ($000's /yr)	% Change	**RTV**($000's /yr)	% Change	**RTV**($000's /yr)	% Change
Young	10.25	-3	8.18	-23	22.94	-7
Normal	10.53	0	10.16	0	24.68	0
Old	13.31	26	17.50	65	26.09	6

Table 3. Results from three different age-class distributions for the clearcut, combined and no-clearcut management scenarios upon annual RTV(000's/yr).

SRF Harvest Scenario	LTSY (000 m^3/yr)	Harvest ($/$m^3$)	Tran ($/$m^3$)	Regen ($/$m^3$)	Total ($/$m^3$)	RTV ($/$m^3$)
Economic Harvest Rules						
Clearcut management	310	25.55	18.72	3.45	47.72	13.41
Constrained clearcut mgmt	235	21.96	18.15	3.18	43.29	27.84
Combined management	235	27.92	19.24	2.28	49.44	16.16
No-clearcut management	115	31.59	16.46	0.04	48.09	26.30

Table 4. Two hundred year average value ($/$m^3$) results for the SRF and the following indicators: maximum long-term sustained yield (LTSY), harvest cost to roadside (Harvest), transportation cost to mill (Tran), regeneration cost (Regen), total delivered wood cost (Total) and delivered wood residual timber value (RTV), produced from alternative management scenarios.

SRF Harvest Scenario	LTSY (000 m^3/yr)	Harvest ($million)	Tran ($million)	Regen ($million)	Total ($million)	RTV ($million)
Economic Harvest Rules						
Clearcut management	310	7.9	5.8	1.1	14.8	4.2
Constrained clearcut mgmt	235	5.2	4.3	0.7	10.2	6.5
Combined management	235	6.6	4.5	0.5	11.6	3.8
No-clearcut management	115	3.6	1.9	-	5.5	3.0

Table 5. Total annual results from the SRF, comparing maximum long-term sustained yield (LTSY), harvest cost to roadside (Harvest), transportation cost to mill (Tran), regeneration cost (Regen), total delivered wood cost (Total) and residual timber value (RTV), produced from alternative management scenarios.

SRF Harvest Scenario	LTSY 000(m^3/yr)	Harvest ($/$m^3$)	Tran ($/$m^3$)	Regen ($/$m^3$)	Total ($/$m^3$)	RTV ($/$m^3$)
Volume Harvest Rules	**Target**					
Clearcut management	375	26.56	43.11	3.57	73.24	-16.20
Combined management	230	36.21	43.69	1.57	81.47	-7.61
No-clearcut management	150	31.83	42.28	0.12	74.23	-1.03
Economic Harvest Rules						
Clearcut management	310	25.55	18.72	3.45	47.72	13.41
Constrained clearcut mgmt	235	21.96	18.15	3.18	43.29	27.84
Combined management	235	27.92	19.24	2.28	49.44	16.16
No-clearcut management	115	31.59	16.46	0.04	48.09	26.30

Table 6. Results from the SRF, comparing maximum long-term sustained yield (LTSY), harvest cost to roadside (Harvest), transportation cost to mill (Tran), regeneration cost (Regen), total delivered wood cost (Total) and (residual timber value) RTV produced from alternative management scenarios.

$$D_v(t) = \frac{r \times V(t) \times [P(t) - C(t) - M(t)] - [V'(t)(P(t) - C(t) - M(t)) + V(t)(P' - C' - M')]}{V(t)} \quad [1]$$

Where:

$D_v(t)$= opportunity cost of delay in harvest at time (t) (in $\$/m^3$)

r = discount rate expressed as a decimal

V(t)= stand volume at time (t) (in m^3/ha)

V'(t)= rate of change in stand volume at time (t) (in m^3/yr)

P(t)= value of the stand's products at time (t) (in $\$/m^3$)

P' = rate of change in value of the stand's products at time (t) (in $\$/m^3$/yr)

C(t)= cost of harvesting the stand's products to roadside at time (t) (in $\$/m^3$)

C' = rate of change in cost of harvesting the stand's products to roadside at time (t) (in $\$/m^3$/yr)

M(t)= cost of transporting the stand's products to the mill at time (t)(in $\$/m^3$)

M' = rate of change in the transportation cost (in $\$/m^3$/yr)

Equation 1: The formula used by Rule_3 to calculate the opportunity cost of harvest delay.

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