DEVELOPING AND TESTING THE APPLICABILITY OF A DECISION SUPPORT SYSTEM FOR THE PLANNING OF JUVENILE JACK PINE THINNING

by

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A CAUTION TO THE READER

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ABSTRACT

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Key Words: decision support system, geographic information system, heuristics, jack pine, network analysis, pre-commercial thinning, remote sensing, spatial analysis.

An investigation was made into the applicability of a model used to assist in planning the allocation of pre-commercial thinning to juvenile jack pine stands. The hypothesis of this study was that planning pre-commercial thinning of juvenile jack pine to focus on areas within a stand (*e.g.* high density areas with the largest potential for response) is cheaper and more efficient than allocating a "blanket" pre-commercial thinning over entire jack pine stands. The model incorporates machine costing models, pre-commercial thinning productivity estimates, stand density maps, and road networks to investigate the potential cost savings of detailed planning of pre-commercial thinning. Integration of a GIS database, remote sensing, and network analysis provided an experimental decision support system (DSS) for planning the allocation of pre-commercial thinning. The DSS was applied to two study areas in northwestern Ontario containing juvenile jack pine stands. Based on the case study results, there appears to be potential for a total cost savings of 12 to 25 percent by planning and focusing pre-commercial thinning treatments to key areas of a stand. Estimated cost savings were reduced as the stem density spatial pattern became more uniform and the average stand density approached the eligible density for thinning. Cost estimates were also found to be sensitive to the pre-commercial thinning productivity estimates. The planning model could be applied to other problems involving spatial components such as skidder trail planning in harvest blocks. Use of this DSS could assist in investigating the interactions between stand density patterns, pre-commercial thinning productivity, pre-commercial thinning equipment operational costs and allocations pre-commercial thinning treatments within a forest stand.

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1 INTRODUCTION

1.1 STUDY PROBLEM

Jack pine (*Pinus banksiana* Lamb.) is the second most important conifer crop species in Ontario and makes up approximately 35% of the total conifer volume harvested from Crown Lands (OMNR, 1991) (Figure 1.1) and almost 60% of artificially regenerated land (Anonymous, 1990).

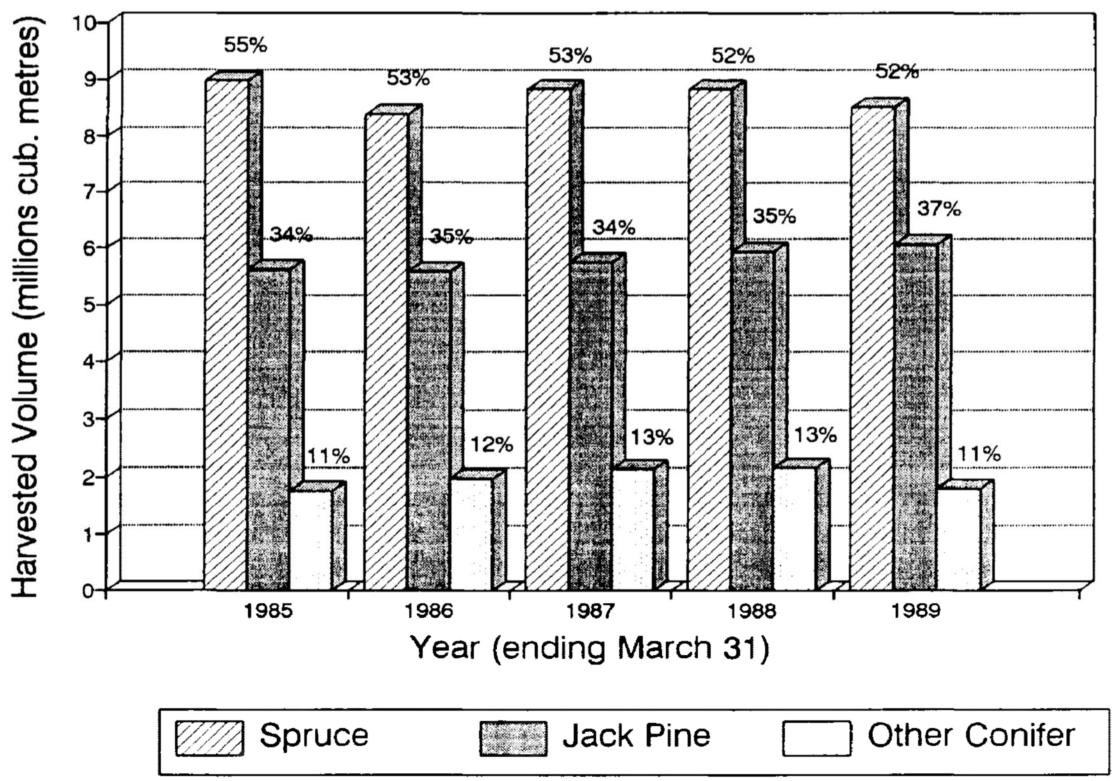


Figure 1.1 Summary of conifer volumes harvested on Crown Lands by spruce, jack pine and other conifer species for the years 1985 to 1989 (OMNR, 1991).

Natural regeneration, aerial seeding, and direct seeding of jack pine can result in dense stands of small diameter trees. Thinning of these stands is intended to reduce the number of undesirable trees and enhance the growth potential of the remaining trees. Also, with a growing concern regarding a predicted shortfall in harvest volumes in the future, pre-commercial thinning (PCT) may reduce the shortfall's impact by shortening the rotation age by approximately 10 years (Litchfield, 1991).

In the past years the OMNR (1991) reports there has been a steady increase in regeneration by seeding methods, but no increase in the amount of land treated with thinning (Figure 1.2). Pletch (1991) estimates that in the Dryden District alone 1,200 ha/yr or more of the regenerated jack pine can be treated by pre-commercial thinning in upcoming years. With so much land potentially requiring pre-commercial thinning, and limited budgets to work with, the thinning treatments must be planned and allocated in the best manner possible.

Morris and Forslund (1991) comment that "traditionally, tending decisions are based solely on qualitative assessments of plantation performance, rather than on quantitative measurements based on sound biological relationships between competition and crop tree growth response." Current pre-commercial thinning planning combines aerial photographs and firsthand knowledge to show areas that require thinning (Pletch, 1990). Designing and applying a decision support system to help in planning, allocating and treating areas with pre-commercial thinning may improve the efficiency and cost of the entire pre-commercial thinning planning process and improve the allocation of funds so that the greatest gains can be achieved from pre-commercial thinning.

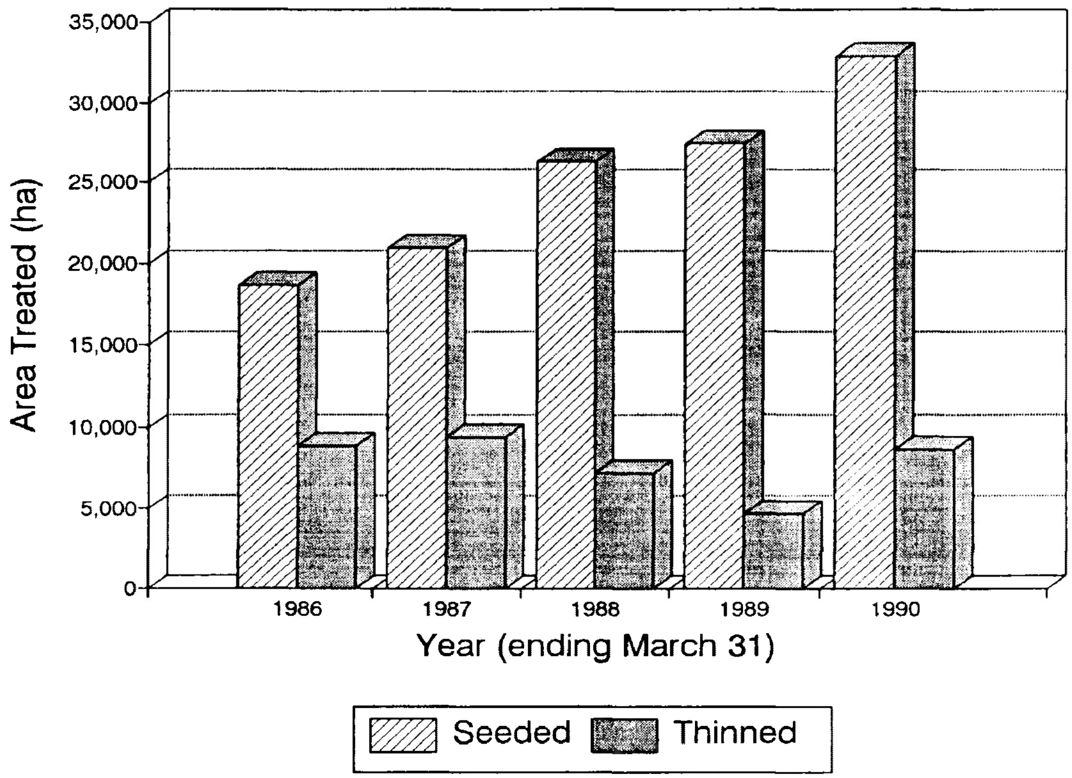


Figure 1.2 Summary of seeding regeneration and stand thinning on Crown Lands for the years 1986 to 1990 (OMNR, 1991).

1.2 STUDY OBJECTIVES AND OUTLINE

The basic hypothesis of this study is that planning pre-commercial thinning of juvenile jack pine to focus on areas within a stand (*e.g.* high density areas with the largest potential for response) is cheaper and more efficient that allocating a "blanket" pre-commercial thinning over entire jack pine stands. Also, a decision support system (DSS) can be developed to aid planning and to demonstrate the above hypothesis. The main objective of this study is to develop and demonstrate a DSS that could assist forest managers in planning pre-commercial thinning in juvenile jack pine stands. This study is not intended to prove the benefits of juvenile thinning over other treatments or study the development of growth and yield curves of jack pine. It is simply a study in operational planning.

2 LITERATURE REVIEW

A major task in constructing a DSS is to achieve a full understanding of the planning problem. The following sections review the many factors accounted for during the development of the pre-commercial thinning planning model. Although many topics and concepts are not linked directly to the DSS, they do form a basis for the model's development. In addition to pre-commercial thinning in jack pine, this planning model also incorporates concepts and techniques of GIS, methods of estimating stem density across stands, procedures for solving location-allocation problems, network analysis for optimizing stand access, as well as estimating productivity and costs for given pre-commercial thinning systems.

2.1 PRE-COMMERCIAL THINNING

Pre-commercial thinning (PCT) is an operation applied to almost pure, dense, forest stands still in the sapling stage (height <5-9 m, or age <15 years, or dbhob <9 cm) where a portion of the stand is eliminated to reduce the average stand density (Dunfield, 1974; NSDNR, 1992). No production of marketable material occurs directly from this operation (Hocker, 1977). The objective of pre-commercial thinning is to increase the growing space available for the residual trees and thereby accelerate their average diameter growth (Anon., 1982; Dunfield, 1974; NSDNR, 1992). Increased growth of the trees would allow for a reduction in the stand's rotation age (Dunfield, 1974; NSDNR, 1992) with a resulting stand composed of an increased proportion of more desirable tree species (NSDNR, 1992).

Objectives of stand thinning include (Alm and Schantz-Hansen, 1970; Axelsson and Routledge, 1970; Day, 1991; Johnstone, 1981a, 1981b, 1982; Ker, 1981; Lavigne and Donnelly, 1989; Selin, 1977; Smith, 1983; Stirling, 1991; Tryon and Hartranft, 1977; and Vassov and Baker, 1988):

1) reduce the stem density closer to that of a mature stand,
2) increase the average diameter growth increment of the stand,
3) increase the yield of dimension and veneer products,
4) reduce the rotation age,
5) maintain a high volume increment of quality wood (increased merchantable volume/ha), however, there is a decrease in total volume/ha and a decrease in total basal area/ha,
6) avoid stagnation of growth,
7) reduce diameter variation,
8) modify species composition with the selection of superior crop trees,
9) decrease mortality of potential crop trees,
10) improve access to the stand,
11) decrease fire hazard,
12) leave trees more vigorous and resistant to diseases, insects and fungi,
13) allow for improved crown form and improved root system (resulting in decreased windthrow),
14) increase light and temperature in stand, leading to increased nutrient production and increased effective growing season and

15) preparation for future silvicultural treatment (fertilization, thinnings).

The effect most often observed with thinning is the increase in average diameter growth increment. Increased average stand diameter is beneficial in final harvest since harvesting production increases as average tree diameter increases and logging costs per unit decrease (Hannula, 1971).

2.2 PRE-COMMERCIAL THINNING APPLIED TO JACK PINE

Jack pine is a tree species suited to even-aged management and regeneration in clearcuts (Sims *et al.*, 1990). It is often managed on very dry and nutritionally poor soils where no other species can effectively grow (Sims *et al.*, 1990). It is an early- to mid-successional (pioneering) species with rapid juvenile growth and is well adapted as a fire-origin species (Fowells, 1965; Sims *et al.*, 1990). Without fire-disturbance, jack pine will eventually be replaced by hardwoods and balsam fir (Sims *et al.*, 1990). It is a shade intolerant species (Sterret, 1920), and as such it grows poorly in closed stand conditions, where it exhibits reduced crown growth (Hosie, 1979). In a closed stand, the live crown becomes reduced and is often less than a fifth of the tree's height (Hosie, 1979).

Jack pine can regenerate naturally after a fire, or be artificially regenerated by planting or seeding. Jack pine regeneration can result in overstocked stands that do not thin well naturally, resulting in dense stands containing small diameter trees (Vassov and Baker, 1988; Nelson, 1990).

Regeneration of jack pine by seeding is usually performed by aerially seeding at 50,000 seeds/ha or site preparation (SIP) seeded at 15 seeds/scalp to achieve a 60% satisfactory stocking level. There is often ingrowth occurring during the early stages of stand development. Seeding can result in grouped, rowed or random distribution patterns (Vassov and Baker, 1988). An investigation by Van Damme and McKee (1990) of the clumping of juvenile jack pine regenerated by different methods of seeding showed that artificial seeding regeneration methods created stands that were more clumped than natural fire-origin stands. The fire-origin stands, however, were producing the highest jack pine density with approximately two to three times the stem density as the artificial seeding methods.

Sims *et al.* (1990) mention that jack pine stands often exhibit "waves of mortality" during the period between 15 and 30 years of age. Also, jack pine stands "older than 22 years have experienced a period of reduced, unproductive growth resulting from competition" (Sims *et al.*, 1990). The potential response in jack pine diminishes rapidly with age (Vassov and Baker, 1988). Also, Cayford (1962) indicates that jack pine crowns recede rapidly in a closed stand, making it is necessary to time the thinning while the live crowns are still large enough to utilize the additional growing space effectively. Therefore it is advisable to thin before 22 years to improve stand growth when the growth response to thinning is most pronounced.

The best time for motor-manual pre-commercial thinning is at a stand height of 1.8 m to 3.6 m after the lower lateral branches have died with the target density around 2500 to 1600 stems/ha (Axelsson and Routledge, 1970; Cayford, 1964; Vassov and

Baker, 1988). However, excessive (heavy) thinning should be avoided since jack pine is susceptible to wind and snow damage (Godman and Olmstead, 1962).

Figure 2.1 shows the effects of pre-commercial thinning on young jack pine stands. Average dbh is increased, total tree height remains unchanged, live crown height is increased and crown width is increased. If the stand is thinned too much, an undesirable branch and stem form can develop in open-grown conditions (Sims *et al.*, 1990).

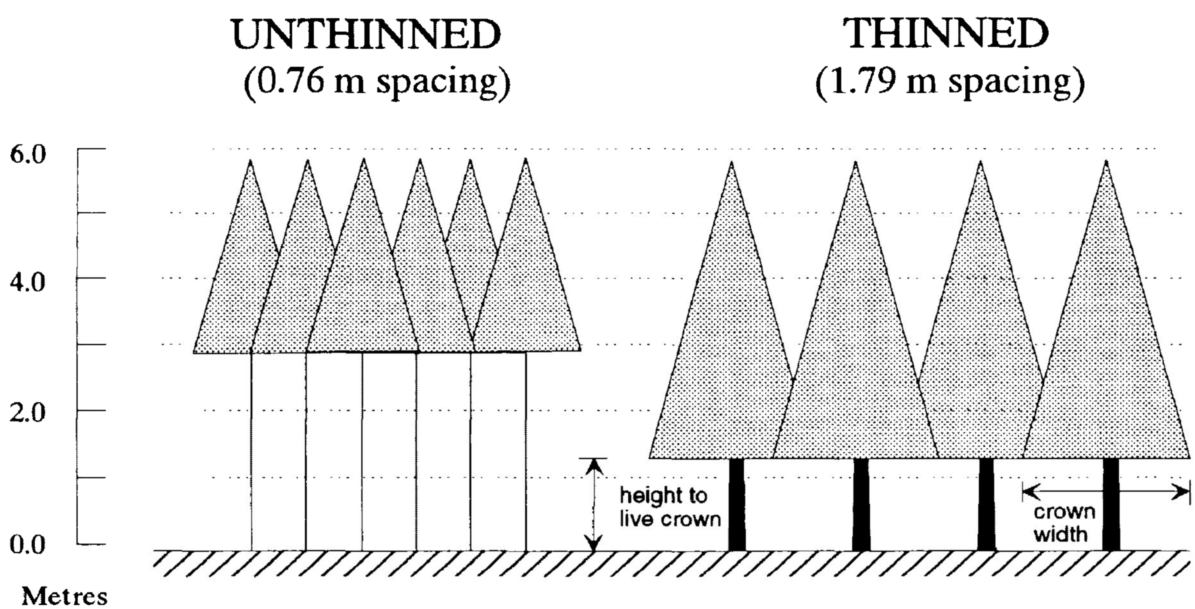


Figure 2.1 Illustration of the effects of pre-commercial thinning in jack pine five years after treatment showing the effects on total height, height to live crown, crown width and dbh (source: Goble and Bowling, 1993).

2.3 FACTORS OF PRE-COMMERCIAL THINNING ALLOCATION

There are many factors to consider in the allocation of pre-commercial thinning. They include (Day, 1991; Morris and Forslund, 1991; Mitchell, 1992; and Vassov and Baker, 1988):

1) management objectives,
2) treatment options,
3) forest stand site index,
4) expected mortality during the proposed rotation,
5) expected treatment response (*e.g.* tree growth, branching form, degree of knottiness in main stem),
6) potential economic gain of enhanced stand growth,
7) current and anticipated timber supply and market situations,
8) distance from manufacturing facilities,
9) availability of capital, equipment and manpower,
10) wood quality as affected by growth rates,
11) cost of prescribed treatment versus the total tending budget and
12) presence of potentially damaging agents.

The ability to perform crop tree selection for a given method is a very important consideration in applying pre-commercial thinning. Crop trees are dominant trees within a prescribed spacing, having low taper, small branch diameters and are relatively free from disease and damage (Vassov and Baker, 1988). The pre-commercial thinning method used must not hinder the selection of good crop trees.

2.4 METHODS OF PRE-COMMERCIAL THINNING

Generally, pre-commercial thinning can be grouped into manual, chemical, motor-manual and mechanical techniques. Manual thinning uses hand axes or Sandvik axes to remove unwanted trees. Chemical thinning (weeding) involves the use of herbicides to kill unwanted trees and competition. Motor-manual thinning involves the use of chainsaws and brushsaws to cut down undesirable trees. Mechanical thinning uses machinery to perform row-thinning, or more recently, to perform selective thinning with boom spacing machines. A more specific description of the methods of pre-commercial thinning include (Vassov and Baker, 1988):

1) Manual thinning: axes, Sandvik axes; allows selective thinning.

2) Chemical thinning: aerial and ground application; with public concerns on the use of chemicals this is currently not a viable technique.

3) Motor-manual thinning: chainsaws, brushsaws; allows selective thinning; brushsaws most effective at ≤ 5 cm diameter, but can handle 8 cm; productivity dependent on density.

4) Mechanical thinning: discs, dozer blades, rakes, drum chopper, mower; row or strip thinning does not allow for selective thinning, however, newer boom-equipped machines do allow some ability for selection; problems with poor mechanical integrity of units, wide prime movers, requiring high stand density to justify and difficult terrain conditions.

2.4.1 Manual and Motor-Manual Pre-Commercial Thinning

Manual and motor-manual treatment are very useful as pre-commercial thinning methods and have the added benefit of providing employment opportunities in regions of high unemployment. Residual stands tend to be of good quality although it is labour-intensive; damage to residual trees is minimal and the total operational cost is fairly low. Manual and motor-manual thinning also have the advantages of individual tree selection, low capital investment and the ability to treat a wide range of stand and site conditions.

The usual tools for motor-manual pre-commercial thinning are chainsaws or brushsaws. The NSDNR (1992) after studying worker productivity using brushsaws and chainsaws concluded that brushsaws were safer and easier to use, and resulted in a 50% higher productivity by professional workers compared to workers using chainsaws. Brushsaws are most widely used in pre-commercial thinning, while chainsaws are used in larger (> 15 cm dbh) and lower density stands, or for smaller scale operations where purchase of a brushsaw is not warranted.

Motor-manual pre-commercial thinning productivity is affected by several factors. A compilation of the factors affecting productivity included (Needham and Clements, 1989; Needham and Hart, 1991; NSDNR, 1992; St-Amour and Ryans, 1992; and Tryon and Hartranft, 1977):

1) initial stand density (considered as the most important),
2) tree species and species composition,
3) tree size (average tree diameter at cut height),
4) variations in stand density,
5) average tree height (significant only for ≥ 5 metres),
6) operator training, ability, motivation and experience,
7) quality of work required,
8) work organization,

9) equipment used,

10) terrain conditions (slopes, obstacles, soil strength) and

11) weather conditions.

2.4.2 Mechanical Pre-Commercial Thinning

The application of mechanical pre-commercial thinning has been initiated with the intent to (Ryans, 1988):

1) increase man-day productivity and decrease costs,

2) offset labour supply problems,

3) decrease risk of injury and improve working conditions and

4) increase quality of work.

Ryans (1988) notes that early studies indicated that mechanical strip thinning lacked selectivity of residual trees and that damage often occurred to residual trees along the cut strip edges. Difficult site conditions (*e.g.* slopes, boulders, stumps, ground strength) were another factor that hampered machine productivity and caused mechanical breakdowns and delays. He also comments that there has been some loss of interest in mechanical thinning in recent years, probably due to the development of the brushsaw to enhance motor-manual productivity and operational flexibility. The use of brushsaws helps minimize risk of injury and improves quality of work and, usually, the availability of labour is not a problem.

A disadvantage of mechanical row thinning is the poor control of crop tree selection. Difficulty in manipulating the cutting head close to crop trees without damage results in decreased selectivity of crop trees (Riley, 1973). Smith (1983) also concluded the main disadvantage of mechanical thinning is the lack of selectivity.

Although mechanical thinning is not efficient in low density stands, it is less sensitive to density than motor-manual methods, making its use advantageous in high density stands (Ryans, 1988). Lower density stands, however, often contain clumps of high density and mechanical strip thinning may not adequately treat these areas (Ryans, 1988).

Mechanical thinning can, however, provide improved stand access when combined with a motor-manual method. Following mechanical row thinning with a motor-manual selective spacing or cleaning removes the additional unwanted trees (Ryans, 1988). After strip thinning, a stand is thinned the next year with motor-manual thinning. The advantage of this method is that it enhances access to site and ensures the removal of unwanted residuals. Using mechanical thinning also creates a well-defined boundary for work areas, which results in improved supervision and control.

Tree selection in mechanical thinning has been made possible by the development of new machinery. A Swedish boom-mounted rotary cutter for mechanized cleaning was described by Ryans (1988). The cutting head is a disk with two free-swinging blades mounted on a hydraulic boom. Ryans (1988) felt that this machine would be competitive in leaf-free periods without deep snow, where the number of stems to be removed is over 20,000 to 25,000 stems/ha.

Stirling (1991) described a mechanical brushing machine designed to clean young plantations of brush species where herbicide use was banned. The machine was a FMG-

0470 4-wheel carrier with a hydraulic boom and a circular cutting head. It was capable of cutting in all directions in an 11-m swath, leaving a 5-cm stump height in areas without rocks. It was estimated that the machine would be competitive in higher density stands (*e.g.* 60,000 to 80,000 stems/ha) and would result in less than 5% damage to the residual crop.

St-Amour and Ryans (1992) describe the results of a study of the Silvana Selective/Ford Versatile cleaning machine. This machine consists of a base carrier, a boom and a cutting head (the same as used on the FMG-0470). The machine was studied during a pre-commercial thinning in black spruce. Strips were thinned perpendicular to the road with most competing vegetation being removed by the machine. The final crop-tree selection was performed by motor-manual crews. Damage assessment showed the highest rate of damage occurred in the taller stand; the shorter stand received 2.4% damage, while the taller stand received 8.2 to 18.0% damage to residual trees. A major cause of damage was nicks and scrapes from the saw (72%) and the guard (28%). The main causes of variation in productivity were attributed to tree height, initial stand density and operator experience.

In the above study, motor-manual follow-up was required for the treatment to meet the thinning objectives. Using the machine only to achieve the target density resulted in excessive damage to the residuals (St-Amour and Ryans, 1992). Costs of operating the machine per productive machine hour (PMH) were estimated at $61.11/PMH when scheduled for 3000 h/annum with 80% utilization. The motor-manual follow-up cost was $161.80/ha for the pre-commercial thinning. Initial stand density seems to be the strongest factor influencing productivity in shorter stands (1.5 m to 6.0 m height) (NSDNR, 1992). St-Amour and Ryans (1992) noticed that productivity of the spacing machine in taller stands was reduced since the machine was unable to drive over taller trees.

2.5 PRODUCTIVITY ESTIMATES

Productivity (ha/PMH) of pre-commercial thinning is largely dependent on initial stand density. Tables of productivity at given initial densities were generated from results reported by NSDNR (1992) and St-Amour and Ryans (1992). This information is summarized in Appendix I. Figure 2.2 shows a graphical comparison of the pre-commercial thinning productivity (ha/PMH) estimates for the brushsaw (NSDNR, 1992), the chainsaw (NSDNR, 1992) and the Silvana Selective/Ford Versatile (St-Amour and Ryans, 1992). Each estimate is based only on the initial stand density with a target density of 3,000 stems/ha. These estimates show that the mechanical spacing is the most productive, but operational costs should also be considered in selecting the most economical method. If the cost of operating the equipment is high it is likely that the mechanical spacing may no be the best option.

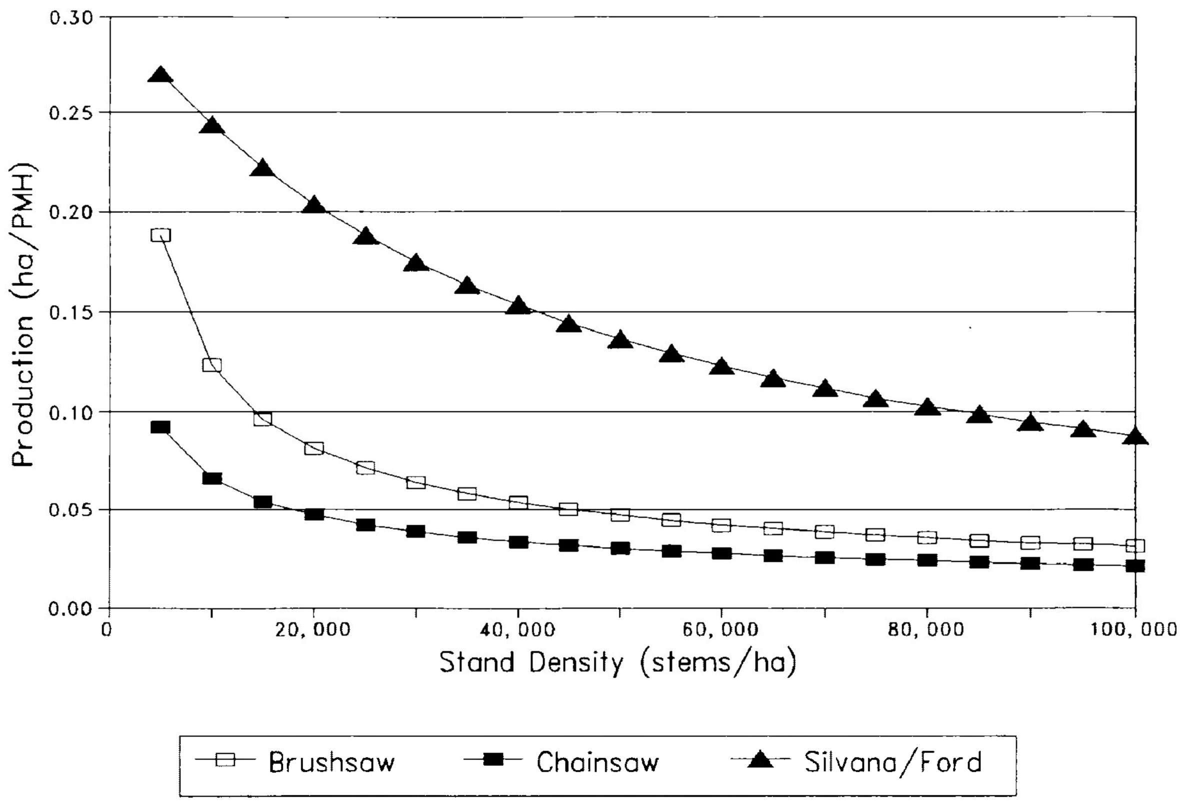


Figure 2.2 Motor-manual and mechanical pre-commercial thinning productivity (ha/PMH) estimates based on the initial stand density for chainsaws, brushsaws and Silvana Selective/Ford Versatile (NSDNR, 1992; St-Amour and Ryans, 1992).

2.6 DECISION SUPPORT SYSTEMS FOR PLANNING IN FORESTRY

A computer model only supplements the manager's own experience, intuition and thought processes (Robak and Prasad, 1985). A decision support system (DSS) extends the range and capability of the manager's decision-making process (increased effectiveness). It basically provides a controlled, supportive tool with no attempt at automating the decision process, predefining the objectives, or imposing solutions (Robak and Prasad, 1985). A DSS may include an optimization model, but still relies on judgement (Robak and Prasad, 1985). The DSS concept when used in forestry combines economic, environmental, silvicultural, technological, political and social constraints into part of the final decision (Robak and Prasad, 1985). As outlined in the preceding sections on pre-commercial thinning, there are many objectives and constraints to consider, with many of them being qualitative in nature. Analysis tools are often useful in such complex systems (Robak and Prasad, 1985).

An ideal decision support system (DSS) has been defined as (Armstrong and Densham, 1990):

1) able to tackle semi-structured problems,
2) easy to use, even by non-computer experts,
3) combines analytical techniques with traditional access to all data and applicable models,
4) uses the models as decision aids,
5) flexible and adaptive to the user's needs and changes in the environment,
6) provides support for all phases of decision-making and
7) operates in a way that is interactive and recursive to provide a multi-pass approach to problem solving.

The use of a DSS is an interactive process (Armstrong and Densham, 1990; Robak and Prasad, 1985).

In order to be cost-effective a DSS should have the characteristics as described by Pulkki (1987):

1) principles employed are understandable and acceptable to the decision-maker,

2) DSS is accessible from the decision-maker's desk,

3) data must be easily updateable,

4) results must be at least satisfactory,

5) useable on the user's hardware,

6) runs efficiently on a personal computer and

7) the anticipated savings must give a sufficient return on investment when compared to the costs (hardware, software, installation, training, operation and maintenance).

With a DSS the operating procedures are structured sufficiently for analysis, but the manager's judgement is essential. The DSS only presents the options, it does not make the final decisions.

2.7 CREATING A PLANNING MODEL

A model is a representation of a real-world situation. Models can take the form of physical models (*e.g.* buildings), symbolic models (flowcharts) or mathematical models. An advantage of a model is it allows the investigation of the system under various set conditions and, in the case of forestry practices, allows non-destructive testing of options. Investigation will allow the decision maker to develop a better understanding of the modelled system. Understanding the problem is the first step towards determining a solution. Taha (1987) describes the steps of an operations research study as:

1) define the problem,

2) construct a model suitable to the problem being addressed,

3) obtain a solution (optimum or satisfactory) of the model,

4) evaluate the model's capability to predict the system's performance and

5) implement the final results with re-evaluation to determine possible system modifications.

Models should be assessed before being placed into regular use as part of a generally accepted planning method. Reasons for assessing a model include (Gass, 1983):

1) the decision-maker is often far removed from the modelling process (*e.g.* government) and needs a basis for deciding when to accept the model's results,

2) the users of a model developed for others must be able to obtain a clear statement of the applicability of the model to the new user problem area and

3) difficulty in assessing the impact of a model's assumptions, data availability and other elements on the model structure and results without a formal, independent evaluation.

Communication of what the model is capable of doing and what its limits are is essential. The designers must describe the assumptions, simplifications and methodologies used by the model (Gass, 1983).

The decision-maker must be comfortable with the method used to analyze a situation. Users that lack sufficient knowledge of the system often have a problem with the model's credibility. This leads to a lack of confidence in the analysis results. In other words, the use of a "black box" method does not improve the credibility, usefulness or utility of a model. A successful model is continuously reappraised to verify that the outputs correspond to reality (Gass, 1983). Validation of a model provides a better understanding of its strengths and weaknesses (Gass, 1983). Some basic steps in model validation include (Gass, 1983):

1) testing the model with test data and/or historical data to check that it performs as expected,

2) check predictions and parameter values,

3) explore the model's predictions, interactions and the relationships between outputs and actual situations and

4) use the model for decision-aiding.

Careful records of predictions and actual results should be kept for reference at later dates.

Sensitivity analysis provides an element of operational validation (Gass, 1983). Varying the values of the parameters systematically over a range of interest will determine if and how the recommended solution changes. Using extreme parameter values and varying one parameter at a time (Gass, 1983) can indicate how finely tuned the parameters need to be (*i.e.* what is sufficient data quality). For example, if the results are not sensitive to wide changes in the parameters, then the need for a finely tuned set of parameters may be alleviated (Gass, 1983).

2.8 GEOGRAPHIC INFORMATION SYSTEMS IN FORESTRY

As part of the collection of planning tools, the geographic information system (GIS) is quickly becoming a part of forest management planning. GIS originated from the efforts of land managers to organize data describing properties such as ownership and natural resources with spatial information (*e.g.* location, area size, and polygon geometry) (Ehlers *et al.*, 1989). GIS has evolved into systems dedicated to storing, maintaining, analyzing and displaying geographically referenced data (Pulkki, 1984).

The data stored in a GIS can include information describing forest cover, road access, hydrology, soil types, topology, precipitation, terrain classification and derived covers (or layers). This data can be stored in either vector format or in raster format (see Figure 2.3). In all, a GIS is a spatial database composed of spatial and descriptive data with each entity described through the use of points, lines or areas (Pulkki, 1984).

Vectors are essentially series of linked points defined by their endpoints. Vectors are capable of representing data as exactly as possible across a continuous coordinate space and therefore are useful for detailed, graphical data (Burrough, 1991; Pulkki, 1984). Vectors are most useful when real-world spatial conditions can be defined as lines or edges, such as a road centre-line (Maffini, 1987).

All linear features are constructed of straight line segments containing two or more coordinates. Thus, arcs can be created to describe features such as roads. These arcs can then be combined to create networks describing a city infrastructure of roads and conduits. Joining the arcs to form closed areas, called polygons, allows the description of entities such as lakes or forest stands.

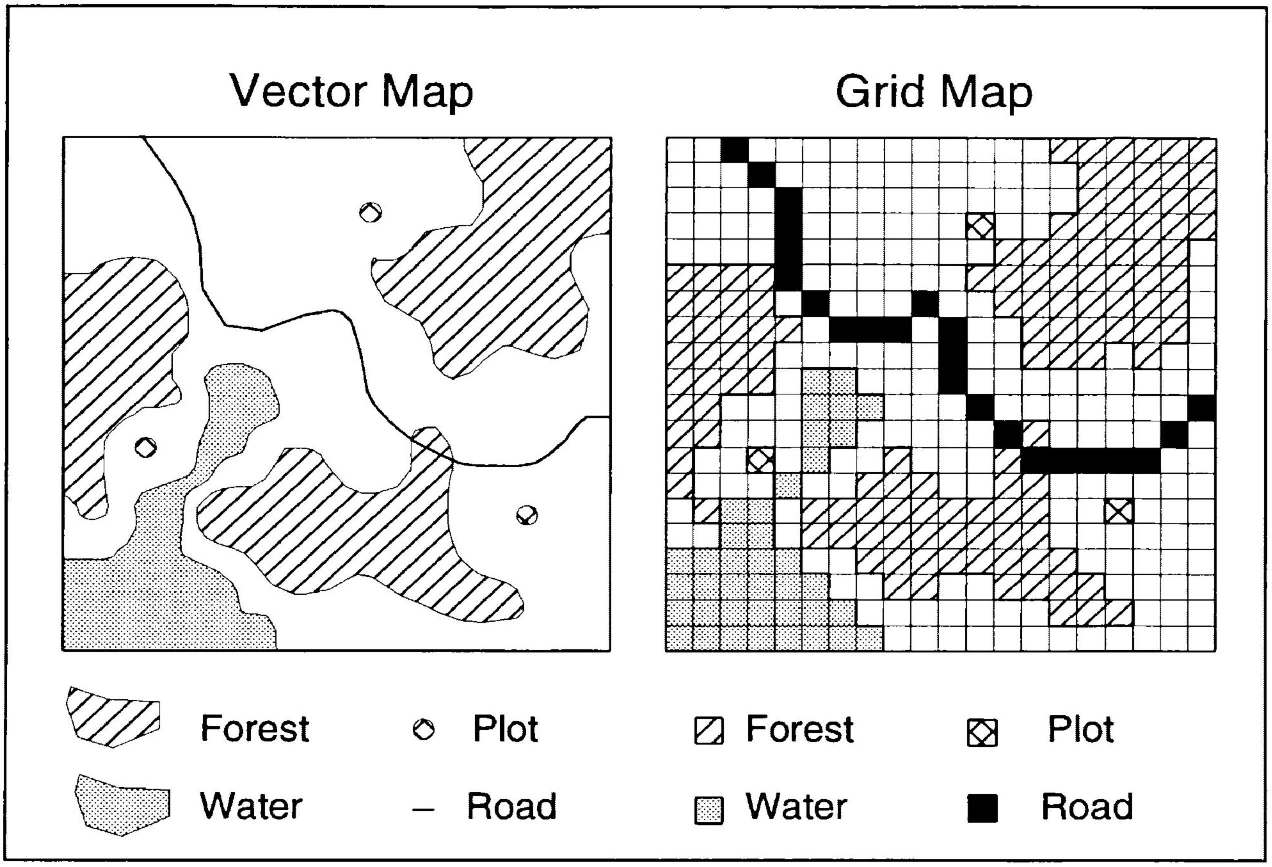


Figure 2.3 Examples of vector data and raster data representing point, line and polygon features.

Raster data is a simpler form than vector data and is easier to manipulate though it tends to require greater storage space than vector data (Dykstra, 1976; de Steiguer and Giles, 1981; Pulkki, 1984; and Maffini, 1987). A raster is a logical record describing a horizontal strip of data, and a grid is a logical record describing a single cell in the data (Pulkki, 1984). Burrough (1991) describes raster data as an array of grid cells (rows and columns). Attributes described by raster and grid data are generally stored as separate sets of arrays, also known as overlays (Burrough, 1991).

A disadvantage of raster data as compared to vector data is in the representation of detail. Grid resolution affects the representation of a two-dimensional surface causing differences in the estimation of length and area (Burrough, 1991). For example, a coarse resolution will not have as exact an area estimate as a finer resolution of the same item, such as a house or property zone.

Berry (1992a) gives an example of the ease of manipulating raster data. He performs an analysis of spatial coincidence by employing various mathematical operations on different data layers (*e.g.* summation, intersection, union, and multiplication). The consistent organization of the cells within the grid matrix allows for a simple process of performing a cell-by-cell operation.

Van Der Laan (1992) describes a raster-based GIS as advantageous over a vector-based GIS in that it is possible to represent virtually all data (vector, attribute, image, scanned maps, digital terrain model) in a raster, and that this structure is suitable for more complex and realistic modelling than is possible with vector formats. Also, with larger storage devices and more powerful processors now available, large-scale planning is now possible with multiple data sources and/or complex modelling operations (Van Der Laan, 1992). Van Der Knaap (1992) presents a set of rules for converting vector data into raster data.

A GIS is a vital tool in analyzing the interactions between spatially distributed resources (Trotter, 1991). Spatial analysis involves detecting and describing patterns and their relationships to other geographical variables (Openshaw and Brunsdon, 1992). These patterns are generally created by similarities among neighbouring observations (Openshaw and Brunsdon, 1992). The main advantage of a GIS in database design is the addition of these spatial components (*i.e.* three-dimensions and temporal). Burrough (1990) states that GIS analyses may be insufficient for spatial analysis because:

1) spatial analysis requires a different set of descriptors than the line-point-polygon,

2) entities in spatial analysis have an uncertainty factor or "fuzzy" attributes and

3) different spatial scales of data create a question as to how they should be combined.

His solution is to use a standard set of rules that combine special purpose modelling systems with generic GIS "toolboxes". This assigns each task to its efficient processor but still allows for the use of standard data formats.

A GIS, therefore, is not the final stage to spatial database management, a GIS is only a tool for presenting spatial data whereas decision-makers require analytical and statistical modelling. The lack of these abilities in current commercial GIS's (Openshaw and Brunsdon, 1992) has resulted in the need for the evolution of the spatial decision support system (Armstrong and Densham, 1990).

The spatial decision support system (SDSS) is essentially a combination of GIS and DSS. A SDSS is a flexible problem-solving tool that is capable of storing, managing, retrieving, analyzing and displaying spatial data (Armstrong and Densham, 1990).

2.9 SOLVING LOCATION-ALLOCATION MODELS

Location-allocation models consist of a set of resources that must be distributed to different destinations according to specified criteria. For example, a forest company must determine how to disperse trucks to haul wood from harvest areas to a mill (or mills) using the most efficient routes. These models use a spatial-choice function that focuses on one or more criteria that are important and performs a spatial search that examines the competing, potential locations for a facility within the operations area. The SDSS can be used to investigate the consequences of using various criteria in defining the eligibility of locations to have facilities, the spatial choice functions used and the relationship of selected centres to their service areas (Armstrong and Densham, 1990).

Two methods commonly used to solve location-allocation models are mathematical programming techniques and heuristics (Armstrong and Densham, 1990). Mathematical programming will provide an optimum solution to the modelled problem, whereas heuristic methods generally result in many feasible solutions from which the most satisfactory is selected (Taha, 1987). An optimum solution is a unique solution for the given situation that describes the best combination of activities needed to attain the problem's objective. A satisfactory solution is intended to satisfy the goals of the decision-maker as closely as possible, though not necessarily in an optimum manner (Taha, 1987). The selection of a specific modelling method will be dependent on the structure of the problem being addressed (Taha, 1987).

Mathematical programming techniques include, among many, linear programming, integer programming and mixed-integer programming. They always yield an optimal solution, but can be computationally intensive. Large problems can therefore require extensive computer time to solve (Armstrong and Densham, 1990). Costs can quickly become prohibitive if solutions are only available in hours rather than in minutes.

Heuristics includes a variety of methods that yield optimal or marginally sub-optimal solutions. Heuristics are an iterative process of finding satisfactory solutions using basic, accepted rules to eliminate unlikely solutions and thereby reducing the problem size to a level that could be solved using an optimization technique. Heuristics rely heavily on experience, inductive reasoning and intuitive and empirical rules to move from one feasible solution to another (Dykstra, 1976; Taha, 1982). Pulkki (1984) describes heuristics as presentation of a series of steps used in solving decision-making problems. Taha (1987) describes heuristics as methods based on rules-of-thumb that are conducive to obtaining a good solution as compared to an optimum solution; normally this requires less computation when compared with exact algorithms. Heuristics are a compromise between making the criteria simple and discriminating correctly between good and bad choices (Pearl, 1984).

The use of heuristics assists in speeding the process towards optimization when used with optimizing algorithms, or assists in finding a satisfactory solution to a problem (Taha, 1987). The advantage of heuristics is they can be used to inexpensively solve large problems that contain many objective functions and provide a range of alternative, marginally sub-optimal solutions (Armstrong and Densham, 1990). A disadvantage, however, is heuristics are generally not robust; there is no guarantee of finding the optimal solution (Armstrong and Densham, 1990).

2.10 ROAD NETWORK ANALYSIS

Parts of the pre-commercial thinning model include road network analysis. Existing roads and trails will be used to access allocated treatment areas. The purpose of road access planning is to minimize the total cost of access. The total cost of road access includes the cost to maintain existing roads, the cost to construct new access roads and new trails within the stand and the cost of travelling off roads and off trails. A simple way to minimize road costs is to reduce the required length of road. This has to be balanced against the road classification; a poorer quality road may not be the best solution if the road is used heavily. Three promising network analysis routines were:

1) the minimal spanning tree (Taha, 1987),
2) the step-wise network creation (Tan, 1992) and
3) the effective proximity surface (Berry, 1992b).

These provide different techniques of analyzing a given network. The minimal spanning tree connects pre-determined nodes to an existing network. The step-wise network creation systematically generates a new network expanding outwards from the existing network. The effective proximity surface derives a network from an analysis of the "flow" patterns created by movement from points of origin to points of destination within a raster-based map. A more detailed description of each of these three methods follows.

The minimal spanning tree is appropriate for networks that do not require loops (Taha, 1987). The algorithm for this method (Figure 2.4) creates a network that resembles the branches of a tree where the branches represent the linking of the nodes to the existing network.

Step-wise network creation as a road planning method is described by Tan (1992). Instead of a "blanket" creation of nodes for the entire image, nodes are created and connected in a step-wise manner based on an existing network. The model searches along the existing network for the best location of the next node. A maximum search radius prevents excessively long links from being generated. Nodes are connected to the existing network as they are found, with the search repeated until constraints (*e.g.* allowable budget) are satisfied or exceeded. One shortcoming of this method is it does not guarantee that all areas within the planning region are searched. The new network is only expanding out from the existing network, therefore it is possible that important areas within the planning region may be missed entirely.

The effective proximity surface is a raster-based map of distances created by the flow from a point of origin to all other points on the map (Berry, 1992b). Distance is calculated from the point of origin based on concentric rings emanating from the origin (*e.g.* wave pattern created by a pebble dropped in a pond) in combination with friction factors for each cell in the map (*e.g.* time to cross, cost of road construction, barriers, slope, *etc.*). Figure 2.5 shows a flowchart of the basic algorithm. Once an effective proximity surface is generated, the optimum path from any point to the origin is defined by following the steepest slope (*i.e.* movement is towards the adjacent cell with the lowest value). It is also possible to determine the volume of flow through each cell by recording the number of times a path passes through each cell (Berry, 1992c).

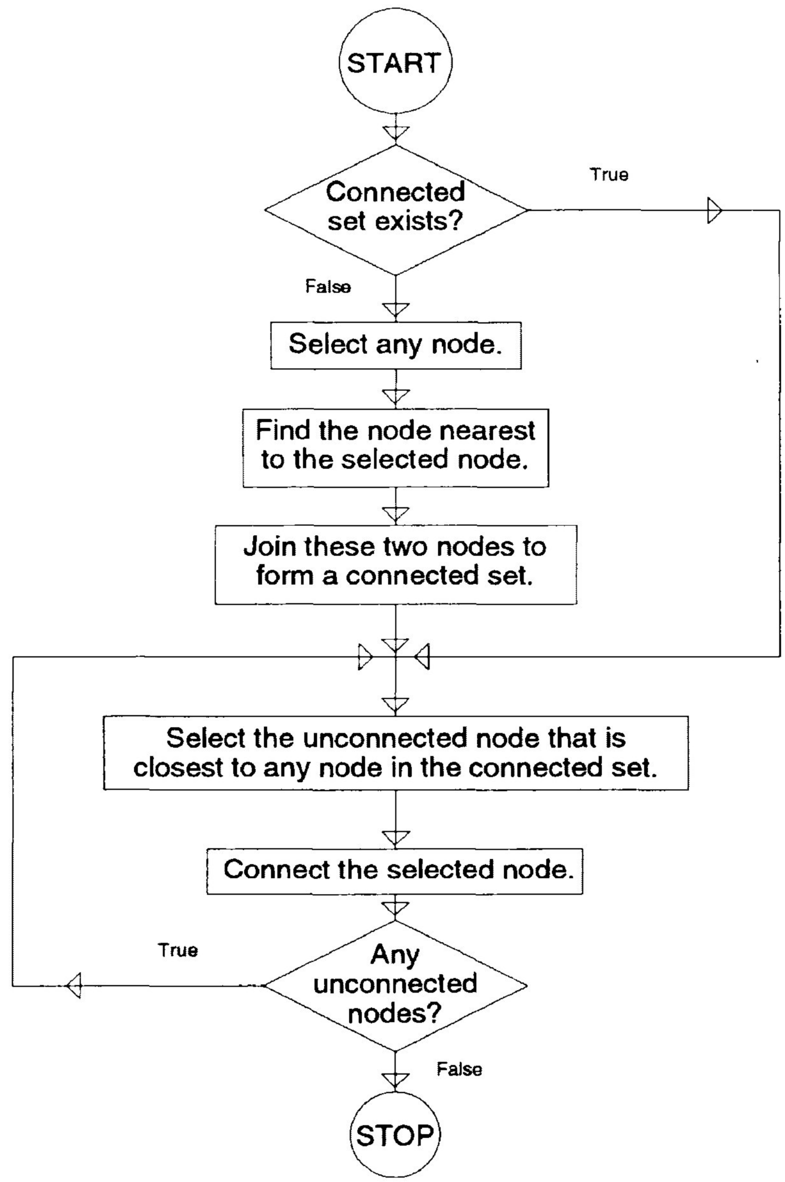


Figure 2.4 Minimal spanning tree algorithm for networks without loops (Taha, 1987).

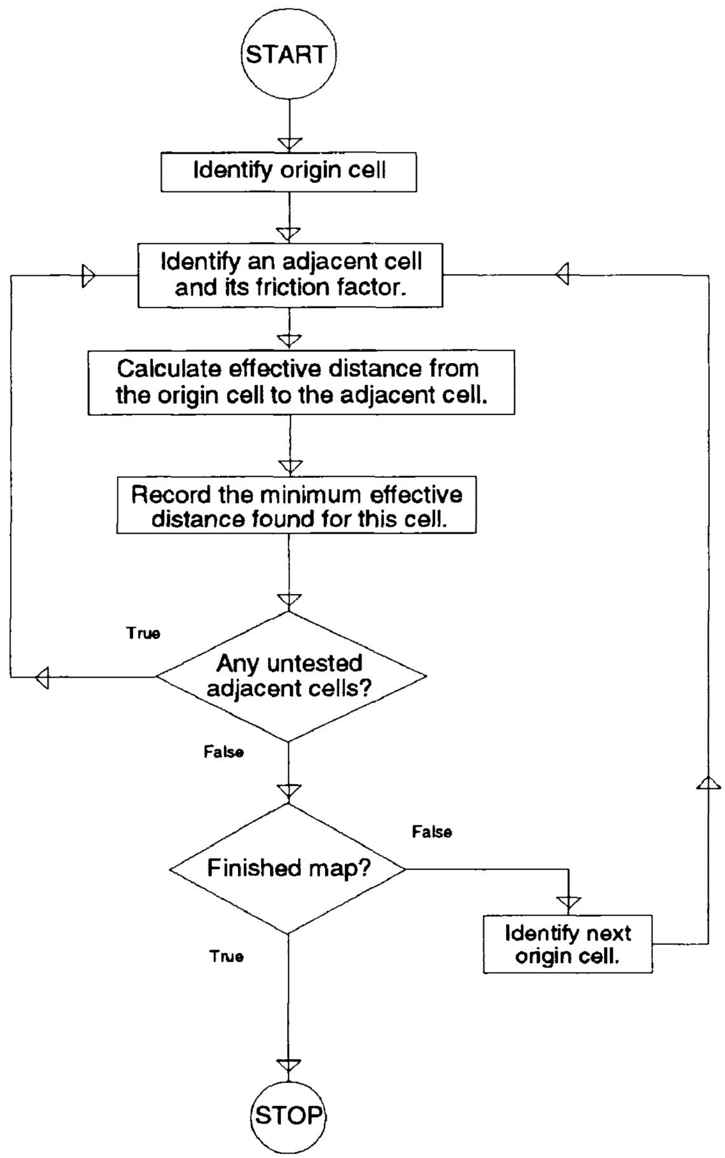


Figure 2.5 Algorithm for determining the effective distance from a point of origin (Berry, 1992b).

This method has the advantage of ensuring the entire planning area is searched for access. However, the repetitive calculations performed across the raster-based map could require extensive amounts of computational time, with the time required increasing exponentially as the map dimensions increase.

A factor that must be considered in describing and planning the road locations in an area is the cost associated with constructing and maintaining each road. Douglas (1986) lists some costs for road construction. Costs varied from $62,000 down to $12,000 per kilometre. Table 3.1 shows some example road types, the code used to describe each and the associated costs.

Table 2.1 Example access road codes, descriptions, accessibility restrictions and construction costs ($/km).

CODE	DESCRIPTION	ACCESSIBILITY	COST ($/km)
0	Null cell	no access to this cell	0
1	Primary road	100 m	45 000
2	Secondary road	300 m	30 000
3	Tertiary/Winter road	200 m	15 000
4	Restricted access	0 m	15 000
5	Water crossing	0 m	20 000

This table only provides a small range of the possible road conditions. For this example, water crossings can be portable bridges, culverts, low water crossings, or some form of temporary structure. Individual codes can be used for each different crossing type if such detail is required for planning decisions.

Factors affecting stand accessibility could include the volume of traffic on the access road (i.e. reduce access along high volume routes), terrain (swampy during summer and fall) and type of equipment being used to treat an area (*e.g.* brushsaws are easier to transport to a site than mechanical spacing equipment).

2.11 GENERATING CONTROL DENSITY MAPS

Most of the data required for the pre-commercial thinning DSS can be obtained from the literature review. However, one of the main data sets required is the spatial distribution of the stem density within the forest stands. This data can be obtained through field sampling, aerial photograph interpretation and satellite image analysis. It would be unwise to develop the pre-commercial thinning planning algorithm based directly on these data. Using only the study data might result in a biased model; the model would essentially be valid only for that specific data set. To prevent the chance of design bias, baseline data sets should be used for the development stages of the DSS model. Using independent test data is a step in validating a model.

The baseline data required is a description of the spatial pattern of density within a population (*i.e.* a jack pine stand) with which to generate a density (stems/ha) grid map. One possibility is to create a simulated forest stand to provide a controlled situation for the development and validation of the algorithm for the planning model.

The primary purpose of using an artificial stand or forest is to provide a controlled "environment" for simulating various experiments. Some examples of using artificial stands are the simulation of harvesting (Newnham and Sjunnesson, 1969;

Newnham, 1970; Newnham, 1966), the testing of sampling designs (Murchison, 1984) and the evaluation of stand thinning procedures (Tymoshuk, 1990).

Murchison (1984) describes three basic forms of testing sampling methodologies in forest stands:

1) real operations in real forest stands,

2) simulated operations in simulated forest stands and

3) simulated operations in "real" forest stands.

The first method of performing real operations in a real forest is expensive in terms of time and money. Also, it can only be performed once in cases such as thinning or harvesting operations. This of course does not allow for any form of sensitivity analysis or comparison of methods under the same conditions.

The second method of simulating operations in a simulated forest stand is cheaper and provides an environment for repeated analyses. Newnham and Maloley (1970) describe the advantages and disadvantages of using computer-generated stands. The advantages include the savings in time and money in obtaining the data, the ability to generate any forest stand conditions given the basic information and the ability to generate a wide and complete range of stand conditions. The disadvantages of computer-generated stands are it is not possible to verify the generated stands are representative of real forest stands and acquiring representative data of a wide range of stands would require extensive surveys.

Artificial forest stands have been generated and used in various studies. Newnham and Maloley (1970) describe a methodology for generating hypothetical forest stands. The generated stands were uniform, random or clumped in their spatial arrangement of trees (Newnham, 1968). The stand created included a spatial pattern of points with tree dbh allocated according to the tree's area of occupancy. Other attributes (total height and crown length) were assigned based on the dbh. The intent was to provide a realistic stand of any desired type for use in simulation studies of harvesting or sampling techniques. However, since a simulated forest probably never exists in the real world and the results obtained may be peculiar to that population (Murchison, 1984) this method has fallen out of favour.

The third method of simulating operations in real forest stand data presents a potentially better solution. Although the data available may be limited, it has the advantage of repeatability using realistic situations at relatively low time and money costs (Murchison, 1984). Instead of generating an artificial forest, real forest data in the form of a stem map (i.e. each individual tree is recorded with x,y-coordinates and descriptive data) is used for the simulation environment. Murchison (1984) used three stem maps from Ek (1969) to examine different sampling methods for sampling bias, precision and cost efficiency. These data consisted of a hardwood stand (16.19 ha) with a clumped spatial pattern, a conifer stand (8.09 ha) with a nearly random spatial pattern, and a red pine plantation (7.28 ha) with a uniform spatial pattern. This provided a real-life case study that could be tested repeatedly. The disadvantage is the expense and time required to obtain map data for a large enough area.

2.12 DENSITY ESTIMATION OF THE PLANNING AREAS

The pre-commercial thinning planning process requires some form of density map describing the study area. Various methods are available to generate this coverage. Data can be compiled from field sampling, but this does not create a continuous representation of the stem density across the stand. A method of interpolating the density values across the treatment area to create a continuous coverage would be more desirable than using simple point densities.

A recommended technique for interpolating the cell values is the inverse squared distance weighting technique (Burrough, 1991; Goodchild and Gopal, 1992; Tomlin, 1990). New cell values are estimated using the following equation (Burrough, 1991):

$$Z(x_j) = \sum (Z(x_i) \cdot dist_{ij}^{-2}) \ / \sum dist_{ij}^{-2}$$

where,

$Z(x_i)$ = value at sample point i
$Z(x_j)$ = interpolated value at point j
$dist_{ij}$ = distance from point i to point j

Estimates using this method tend to be susceptible to clustering of the original data points (Burrough, 1991). Interpolation can be performed using either a fixed window size (*i.e.* maximum distance from the interpolation point) or using a fixed number of sample points. Fixed window sizes tend to use four to twelve points for the estimation (a result of clustering). Using a fixed number of sample points will make no difference to estimation if the samples are regularly spaced, but for an irregular spatial distribution of samples each interpolation will be made across an area of different size, shape and orientation (Burrough, 1991).

2.13 SYSTEM OPERATION COST ESTIMATES

Cost estimates of operating the pre-commercial thinning equipment are also necessary portions of the pre-commercial thinning DSS. Estimates are based on various parameters in a system costing model (Rickard and Savage, 1983) as described in Appendix II. The equipment's initial cost outlay, expected life, cost of operation, maintenance and availability are combined to estimate the total cost and total productivity per hour of each piece of equipment.

3 METHODS

The utility of the DSS and the planned pre-commercial thinning was tested by comparing the thinning cost estimates to those derived from a simple "blanket" method. Comparison is made with different methods of designing the allocation and with different pre-commercial thinning equipment.

Compilation of data was a major component of the development. Data was required for the density estimates, for the pre-commercial thinning cost estimates and for the thinning productivity estimates. The model also requires data describing the spatial location of stem density (stems/ha), road access, thinning system costs per productive machine hour ($/PMH) and thinning system productivity (ha/PMH) relative to stem density. The completed DSS integrates these data types to create a proposed treatment allocation within the stand.

During the model development stage a method was also developed to generate hypothetical stands. These hypothetical stands were used in the development and calibration of the DSS algorithm.

3.1 STUDY AREAS

The study areas included some forest stands near Raith, Ontario and a larger area near English River/Martin, Ontario (Figure 3.1). The areas were chosen for their large component of jack pine. Regeneration of the Martin sites consisted of aerial seeding.

The Raith sites were bladed and seeded. Systematic sampling was performed in both study areas in several juvenile jack pine stands to estimate stem density.

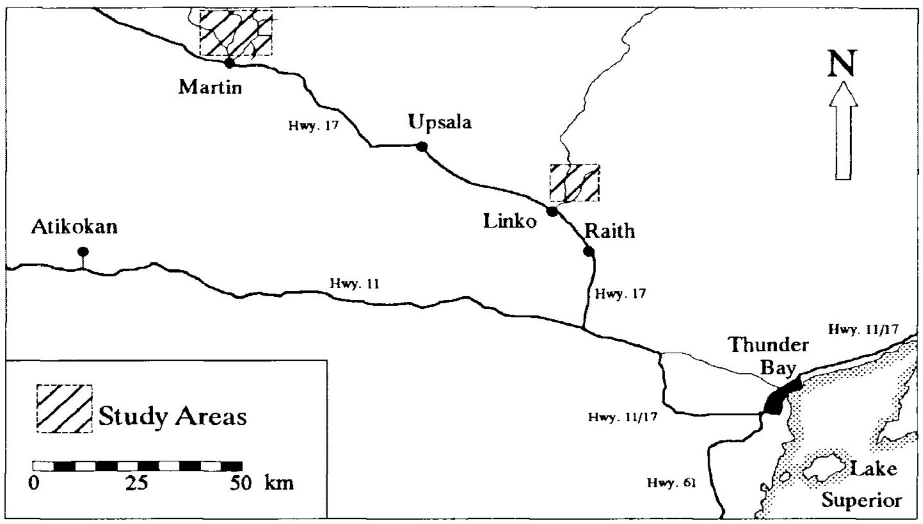


Figure 3.1 Study area locations near Raith and Martin in northwestern Ontario.

3.2 PLANNING MODEL DEVELOPMENT

The pre-commercial thinning DSS brings the data together to present planning opportunities. The data includes the initial stem density, the initial road access and the pre-commercial thinning system's operational cost and productivity. The analysis results present possible allocations of pre-commercial thinning while trying to minimize the required travel distance from roads.

The pre-commercial thinning model is written using Microsoft FORTRAN version 5.0 for use on a MS-DOS personal computer. This version of FORTRAN allows the incorporation of graphic displays and the integration of the Microsoft C programming language. The entire program is controlled through an ASCII text configuration file defining the model's analysis parameters. Table 3.1 presents a sample configuration file listing. The use of configuration files allows the creation of batch files for performing sensitivity analyses.

Table 3.1 Sample configuration file listing.

```
FILE: SAMPLE.CFG                                                DESCRIPTION
CONFIGURATION FOR EXAMPLE DATA.
------------------------------------------                      -----------------------------
PCT MODEL INPUT FILES.
DENSITY GIS FILE:                 density.gis      =            stand density grid map
ROAD ACCESS FILE:                 oldroad.gis      =            stand access grid map
ROAD BUFFER DATA FILE:            roaddata.dat     =            off-trail access distances
PRODUCTION ESTIMATES:             sample.pct       =            PCT productivity estimates
EQUIPMENT SYSTEM COSTING MODEL:   sample.cst       =            system costing model

PCT MODEL RESULTS FILES.
LOG FILE:                         sample.log       =            output/report file
INITIAL ACCESS BUFFER:            buffer01.gis     =            initial accessible area
NEW ACCESS BUFFER:                buffer02.gis     =            PCT planned allocations
NEW ROAD ACCESS:                  newroad.gis      =            new stand access grid map

CONFIGURATION.
MIN.DENSITY  :   3000                              =            minimum eligible density
MAX.DENSITY  : 999999                              =            maximum eligible density
SCREEN PAUSE : N                                   =            screen pause (ON/OFF)
GRAPHICS     : N                                   =            display graphics (ON/OFF)
MIN.NODE AREA:    0.25                             =            minimum eligible area in a node (ha)
DENSITY CONV.: 1000.0                              =            density class conversion factor
                                                                (stems/ha)
NODE INTERVAL:   10.0                              =            search interval between nodes (m)
```

All spatial data were stored in ERDAS© GIS file format, where data values are recorded as an integer value between 0 and 255. The integer nature of the GIS files required that density values be coded into classes. The density classes used for the analysis can be described by three basic categories of null class, background class or density class.

CELL VALUE	CLASS DESCRIPTION
0	Null cells (not part of the study area).
1	Background cell (inside study area, but not eligible for treatment).
2	Density class (0 stems/ha).
3	Density class (1 to 1000 stems/ha).
4	Density class (1001 to 2000 stems/ha).
5	Density class (2001 to 3000 stems/ha).
etc.	

Density classes do not have to represent 1000's of stems/ha. A conversion factor can be defined in the configuration file. For example, instead of 1000's of stems/ha the classes can be defined as 100's or 10 000's of stems per hectare.

3.3 ALLOCATION ALGORITHM

The pre-commercial thinning allocation algorithm follows four basic steps. The DSS first determines currently accessible regions within the study area. Step two locates areas that still require pre-commercial thinning. Step three connects these regions to the existing roads and trails using network analysis. The final step estimates the pre-commercial thinning operation costs for the allocated area. As a comparison, the cost is also estimated for the entire image ("blanket" allocation).

Initial accessible area (step 1) is determined from the initial access map and the defined buffer distances for each road/trail type. All cells within the defined buffer distance are allocated to pre-commercial thinning, including densities below the eligible cut-off. Low density cells are included in the allocation calculations as it is assumed the pre-commercial thinning operation must meet the target density throughout the post-treatment stand. In order to ensure the target is satisfied, the operator will have to progress through all areas within the allocated boundaries to ensure no dense patches are missed. Untreated dense patches could result in penalties to the contractor for failing to meet the terms of the pre-commercial thinning project.

After the initial access areas are determined, the DSS determines which regions still require pre-commercial thinning (step 2). Allocation of pre-commercial thinning to these areas is determined using a search routine that selects eligible regions within the stands based on user-defined parameters. These eligible regions are nodes describing the centre-point of pre-commercial thinning within a given radius. Node selection is controlled by:

1) Search radius (m): defines the distance to search from the current centre-point for eligible regions.

2) Minimum density (stems/ha): defines the minimum density required for pre-commercial thinning to occur.

3) Maximum density (stems/ha): optional, this defines the upper limit of stem density for pre-commercial thinning. This can be used to limit thinning to cost-effective densities, or where the potential growth response justifies thinning.

4) Minimum area (ha): defines the minimum area within the search radius that must be covered by eligible density in order for the node to be allocated for pre-commercial thinning.

5) Node search interval: this parameter was included to search larger density images. It defines the step interval (m) used to search across an image. A value of 0 will cause every cell in the image to be searched; values greater than 0 will cause the search to step across the image that many metres. This decreases the computational time required to find nodes in a large image, although a greater value also reduces the thoroughness of the search.

Figure 3.2 illustrates eligible nodes and ineligible nodes. The search is an iterative process that selects nodes if they contain greater than the minimum area of eligible density. Each pass selects the node with the most area of eligible density (Figure 3.3). These eligible regions are added to the list of new nodes found in the image. To ensure this region is not allocated again, all cells surrounding this node cell are removed from the image. The search continues until no more eligible nodes are found in the image.

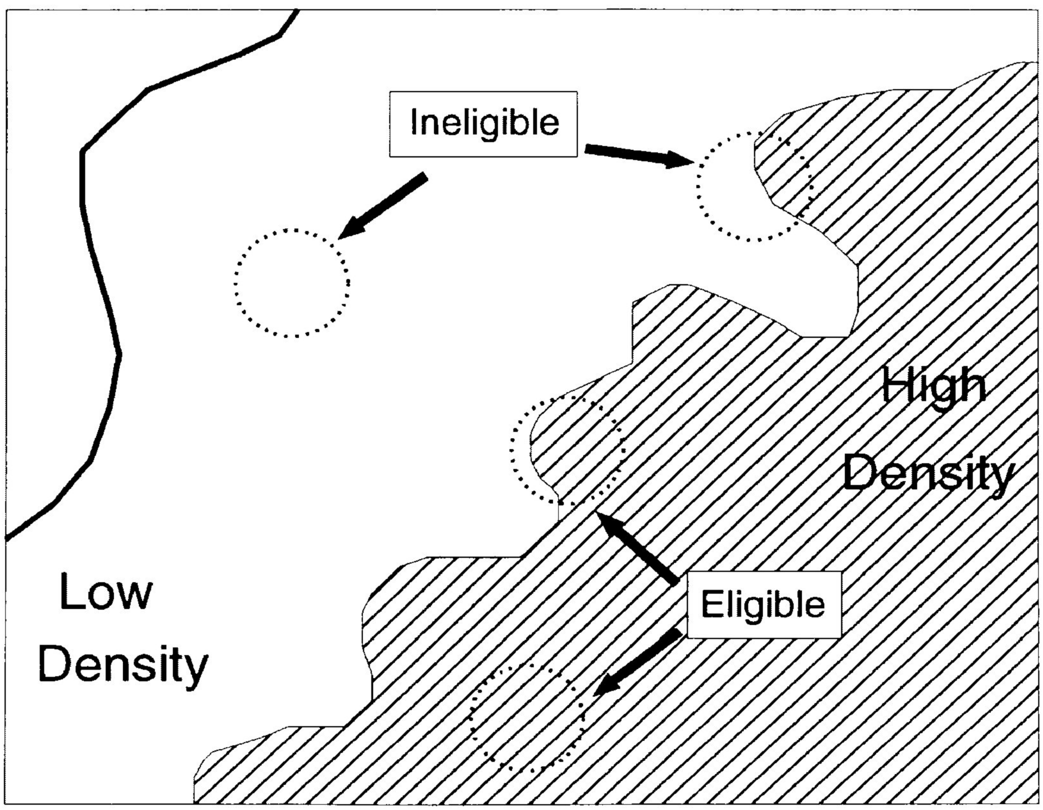


Figure 3.2 Node selection within a stand of high and low density patches illustrating eligible regions for pre-commercial thinning.

All nodes within the image are recorded in a list that can be passed on for connection to the existing road network. These nodes are connected iteratively to the initial road network (step three) using the minimal spanning tree algorithm. The minimal spanning tree was chosen for speed in determining the optimum network for the allocated nodes. This network represents access trails for the pre-commercial thinning crews. These trails, once thinned, provide easier access into the stand as well as a point of reference for the crews.

After all nodes are connected another cost estimate is generated for all cells accessible from this new trail network. Again, all cells within the defined buffer distance are included in the calculations. This creates a network of pre-commercial thinning corridors that connect all the pre-commercial thinning nodes.

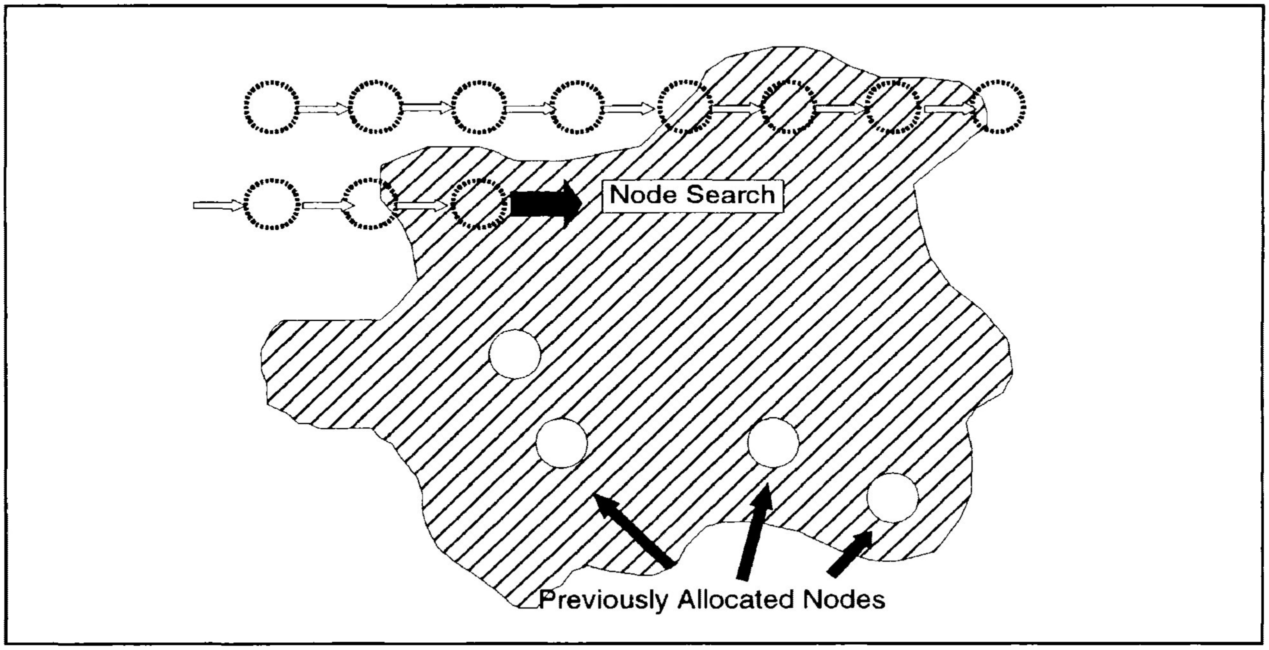


Figure 3.3 Search for the node with the maximum amount of eligible area within the density image.

In addition to displaying planning results on the screen, the DSS also records results in user-defined ASCII text file. An example of a report file is presented in Appendix III. Reported statistics for the spatial density maps include:

1) average density (stems/ha),
2) density variance,
3) minimum and maximum values and
4) cell count.

Statistics are calculated only for the cells within the stands. Null or inaccessible cells are not used in the density computations as they describe areas such as lakes, rivers, roads, or areas of concern where access is restricted.

The report also lists three cost estimates for pre-commercial thinning of the planning area describing the cost of thinning the entire original density map, the cost of thinning the currently accessible areas and the cost of thinning the proposed planned access areas. Each cost estimate lists by density class, the stand area (ha) thinned, the cost of the pre-commercial thinning system at that density ($/PMH), the estimated time to complete the thinning for that density (PMH) and the estimated cost of thinning that density ($). The density classes are subdivided into "below eligible density", "eligible density" and "above eligible density".

3.4 FIELD DATA FOR THE PLANNING MODEL

The pre-commercial thinning model requires various data for its analysis. Data includes stand density grid maps, road access grid maps, pre-commercial thinning system costing models, pre-commercial thinning productivity estimate models and cost estimates for access road construction and maintenance. Stem density was obtained by performing a systematic sampling of the juvenile jack pine stands at Raith and Martin.

Circular plots (50 m^2) were sampled at 50-metre intervals along parallel lines located across the stand (Figure 3.4). Plots on adjacent lines were offset by 25 metres along the line. This gave a 2% sampling intensity. Measurements included number of trees of each species present and an estimated average tree height for each species. These field data were then used to estimate the stem densities within the planning area. The time required to measure the plots (including walking between plots and establishing the plot) was approximately one every six minutes, or 2.5 h/ha. For a worker hired at a rate of $12.50/h (including fringes and employment expenses) for an 8-hour day (less

1 hour for return travel to the site), plus transport to the site (assuming $10/worker/day), the cost is approximately $6.30/ha.

The field data describes of the current stand densities. Since this data was collected at regular intervals across the stand it can provide a more detailed pattern of the density than is available from FRI stand information.

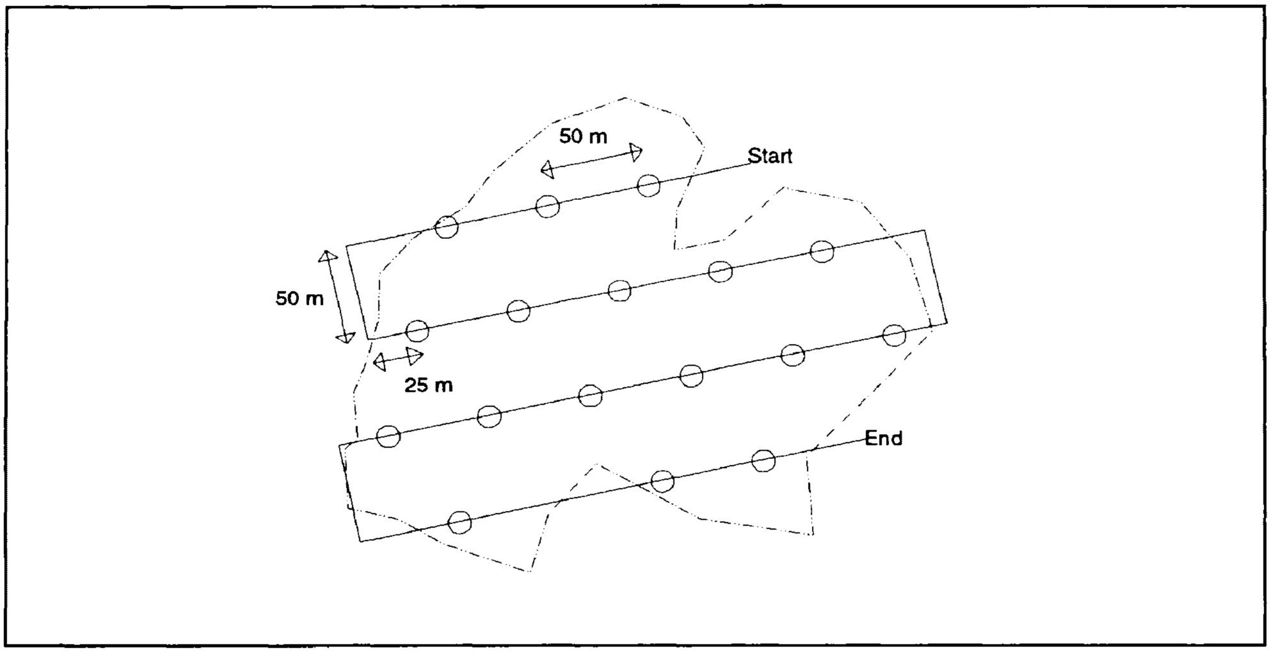


Figure 3.4 Systematic plot location within a stand.

3.5 BASELINE GRID MAP DATA

The main intent of generating an artificial forest for this project is to create a controlled spatial pattern to develop and test the planning algorithm before analyzing some operational data. Therefore, any flaws and/or shortcomings in the model can be corrected without creating any bias that could result from using the operational data (*i.e.* the algorithm is unaffected by the state of the operational data). If the study site data were used to develop the model then there is the problem of the frame of reference (validity of the model for other populations). The use of the artificial data provides a training ground for testing the model's validity and sensitivity. It also provides a subset of data for debugging and estimating the model's efficiency (time to run, storage space required).

Stem map data provides a good basis for a description of the distribution of stem density across a stand. Stem map data was available from a study in a jack pine stand near Thunder Bay (Pulkki and Goble, 1991) that included x- and y-coordinates of individual trees of all species within the plots. The plots covered a contiguous area of 40 metres by 120 metres (0.48 ha). It was felt that a description of a larger area would be more useful for the development stages of the model. Some possible methods of creating a larger forest area from the stem map data include:

1. Mirroring the data sets (or "flipping") to create a larger area of forest.

2. Segment the data into square subsets or tiles (approximately 40 m x 40 m per tile) and randomly select a tile and place it in a large mosaic. To provide some form of uniqueness each tile is placed with a random factor of 90 degrees of rotation (*i.e.* 0, 90, 180, or 270 degrees).

3. Another possibility is to use the data sets in their original form and generate an enlarged density grid map. An estimate of the density for each square metre (1 m x 1 m) in the data will represent a theoretical forest area of 10 m x 10 m (0.01 ha).

Flipping (or mirroring) the data sets is simple to achieve. The resulting map, however, is not adequate as there is a definite pattern across the "mirror" seams. For example, the stem map data generates a repeated diamond pattern as in Figure 3.5.

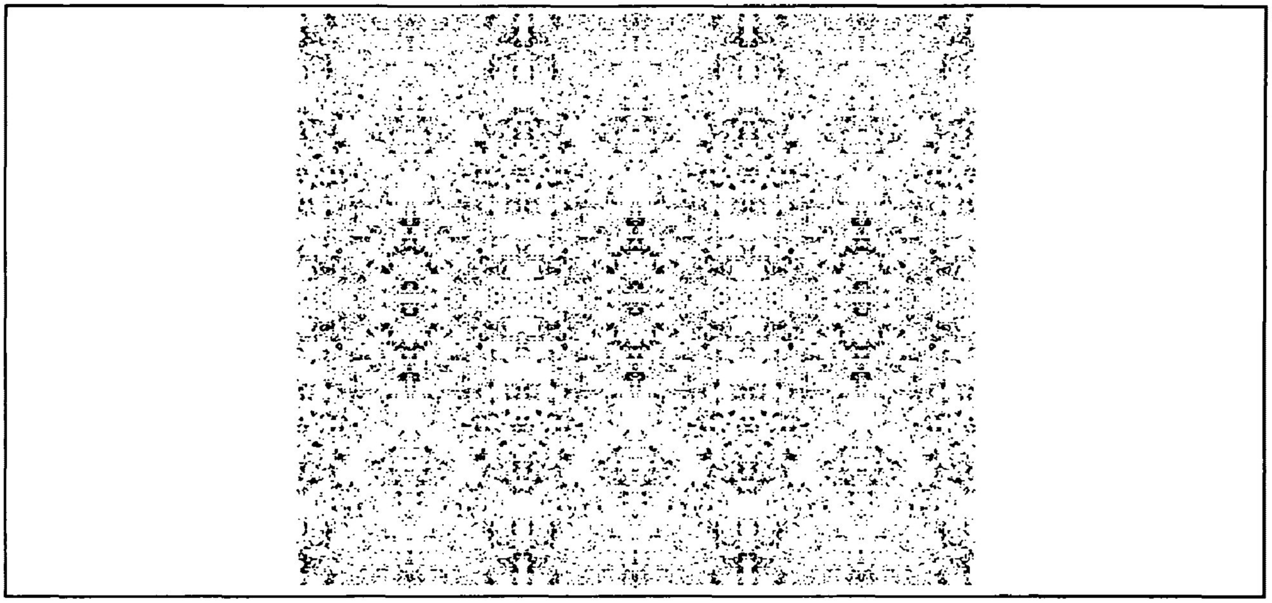


Figure 3.5 Large stem map created by repeatedly flipping (mirroring) the original stem map data set.

Generating a mosaic would alleviate the creation of obvious repetitive patterns, but there are abrupt changes across the tile edges (*i.e.* no association of individual tree dbh with respect to tree growing space). It can, however, create a large stand area based on real stand data (Figure 3.6).

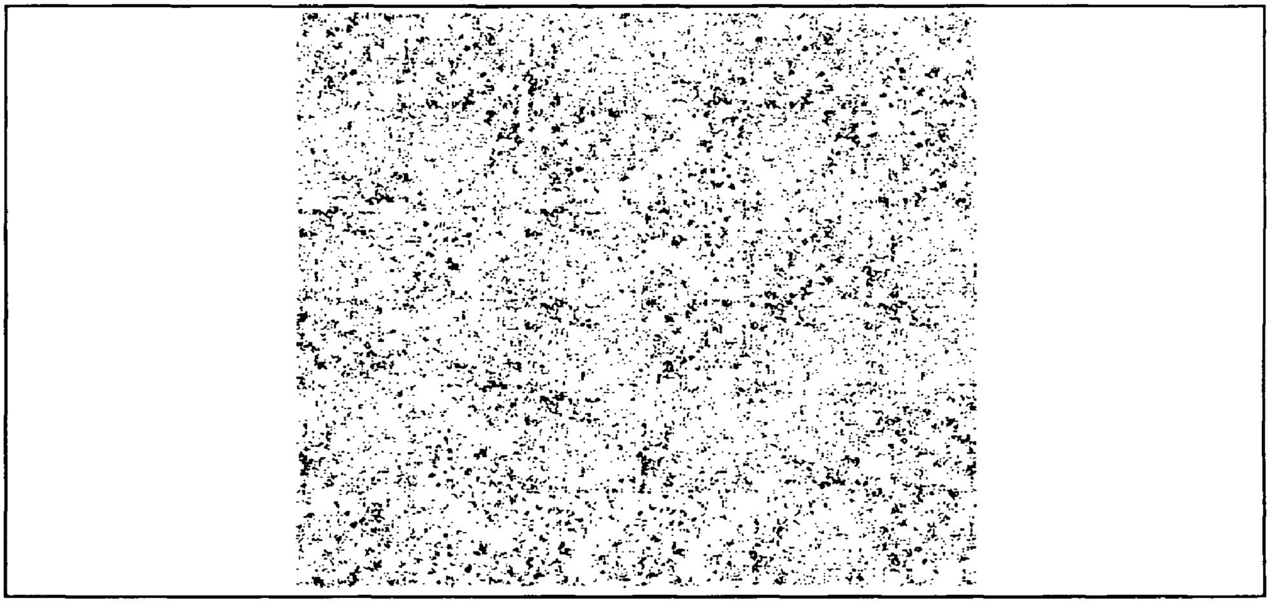


Figure 3.6 Large stem map created using a random mosaic of subsets of the original stem map data set.

The enlarged density map avoids the creation of new edges. Each cell essentially represents a larger forest area in the theoretical forest. Density (stems/ha) was estimated from the average distance to the nearest five trees. The original stem mapping data (the 40 m x 120 m jack pine stand) was divided into three equal portions (40 m x 40 m) to provide three smaller data sets (Figure 3.7). Each of these sub sets was used to create a baseline grid map. These three grid maps created density images of 100 rows by 100 columns in size for use as the baseline spatial data for the developmental stages of the pre-commercial thinning planning model.

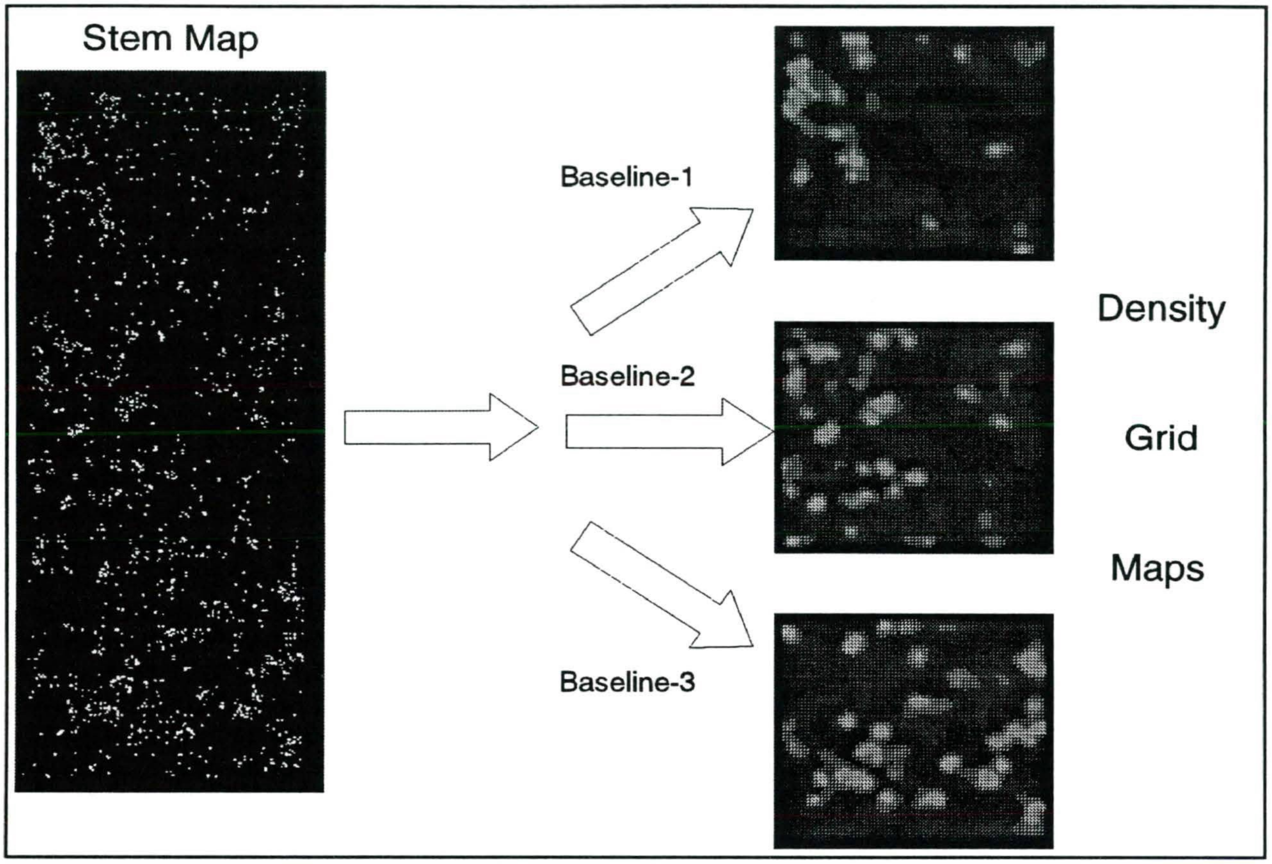


Figure 3.7 Stem map data divided into three density grid maps for use as the control/baseline data for developing the planning model.

Use of the stem map data has the advantage of describing exactly what is on the ground, providing accurate and detailed stand characteristic data that is not available from the FRI for the study site.

3.6 CASE STUDY GRID MAP DATA

The case study polygons were derived from stand boundaries obtained from the FRI data available on the ARC/INFO GIS. These data were initially in vector format, and were converted into a raster format for the actual analysis. Figure 3.8 shows the ARC/INFO vector map of the Raith study area.

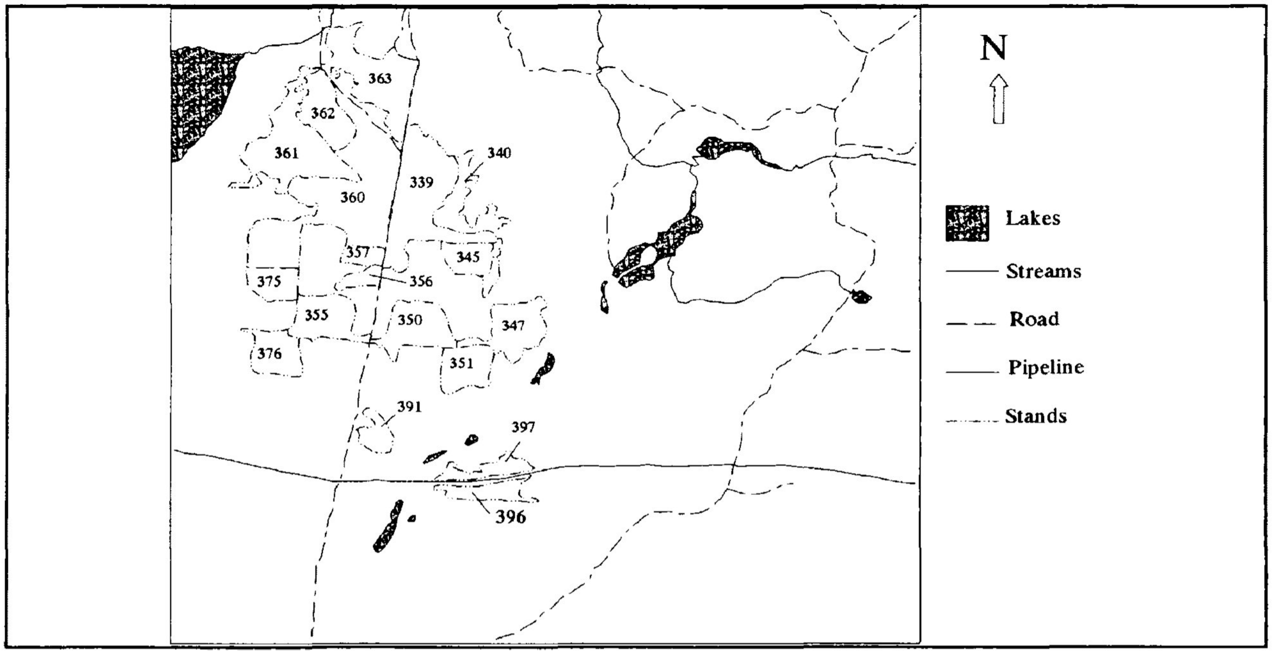


Figure 3.8 Raith study area showing jack pine stands, road access and water.

Stem densities within the study planning areas were approximated at different planning resolutions from the field data:

1) Polygons derived from aerial photography: density was calculated as the average plot density within each polygon (called CIR photo).

2) Individual cell/pixel: density was determined cell-by-cell in one of two ways. The first method used only the density of the nearest field plot (called Nearest Neighbour). The second method interpolated the density for each cell from surrounding field plots (called Interpolated).

Systematic field survey data gives a good description of the stem density at each plot location across the stand, but it does not indicate the density found between plot locations (*i.e.* it does not provide a continuous surface). To obtain these between-plot values some method is needed to estimate or interpolate the cell values between plot locations on the grid map.

One method of estimating the density for cells between plots is to simply assign the value of the nearest plot to create Thiessen polygons of the stem density. This nearest-neighbour method, however, does not account for changes or gradients in values between locations. An example of the result of using a nearest-neighbour method is seen in Figure 3.9 for the Raith study area.

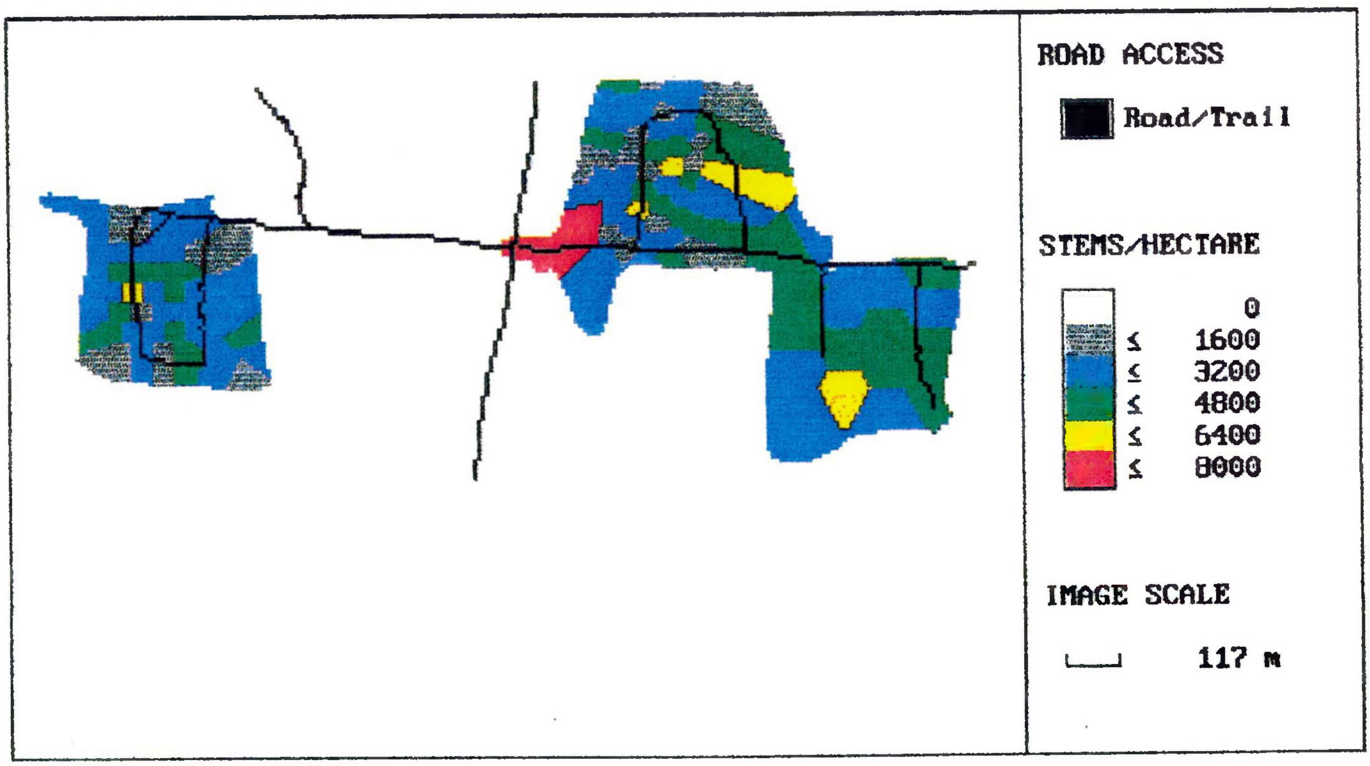


Figure 3.9 Raith jack pine blocks with cell values derived from the field plot data using the nearest-neighbour method.

As an alternative, density values were also determined as a gradient between plots using the inverse squared distance weighting technique. Since sample points for the field data were collected at regular intervals the interpolation was performed using a fixed number of sample points. Figure 3.10 shows an example of the interpolated values within the sampled jack pine stands at Raith. Note that compared with the nearest-neighbour method the resulting cell values change gradually.

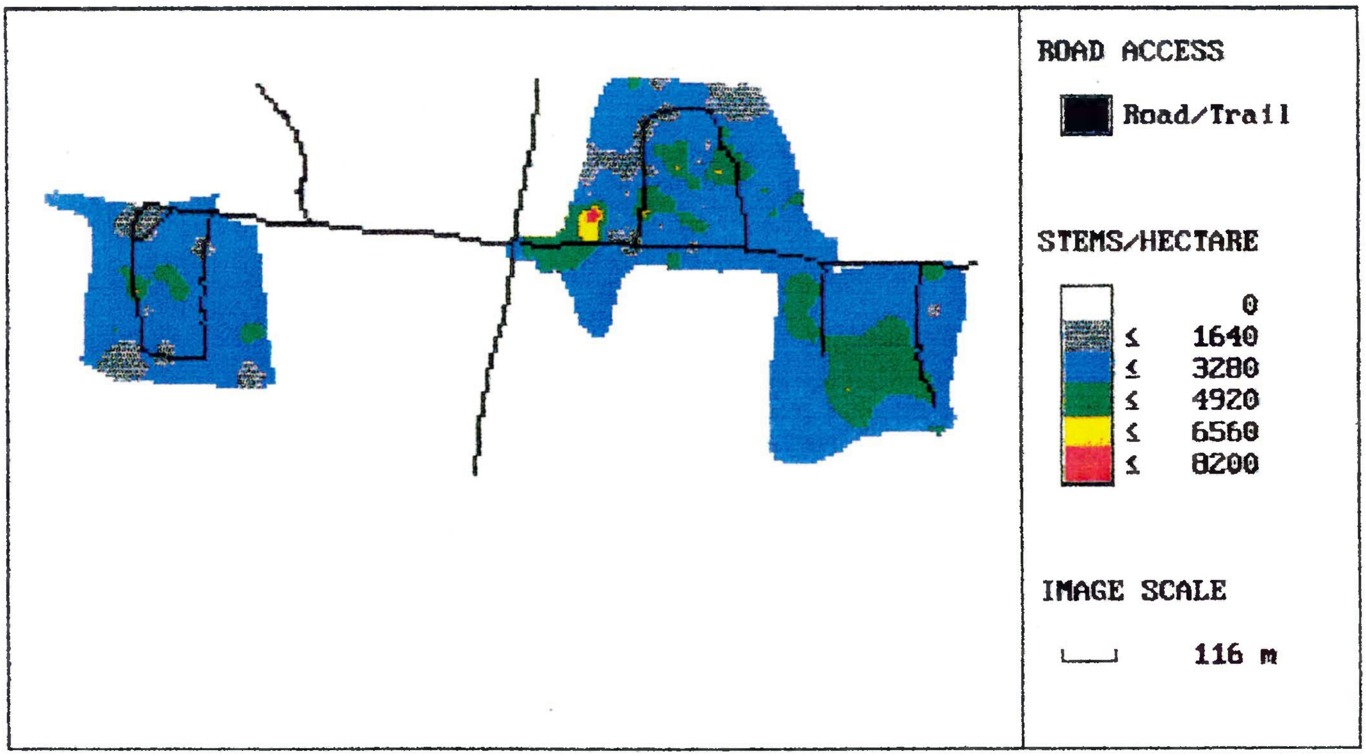


Figure 3.10 Raith jack pine blocks with cell values derived from the field plot data using the inverse squared distance weighting technique (interpolated).

3.7 STAND ACCESS GRID MAP DATA

Stand access maps, like the stand boundary maps, were derived from FRI coverages and photo interpretation. Road access maps were stored in the ERDAS© file format with integer codes describing different road types. Each cell represents the position of the road centre-line as estimated from the data source. The codes for each cell can describe the road quality and access limitations from a road (*e.g.* stream crossings and protected areas).

In planning the thinning allocations, allowable off-trail distances (or buffer distances) are used to describe the maximum allowed distance in metres that pre-commercial thinning allocation can occur from a given road or trail type. These are intended to represent the maximum off-trail travel distance for a given pre-commercial thinning system (*i.e.* brushsaw operator or thinning machinery) from a point of access. During the cost estimation phases of the planning model all density cells within this buffer distance are "allocated" to pre-commercial thinning and used to estimate a productivity and cost of thinning.

The trails created by the planning model are simply marked pathways or swaths cut through the stand. They are incorporated as part of the pre-commercial thinning operation. A supervisor would mark the trails prior to thinning, and the operator(s) would follow afterwards. Creating these trails provides easier access for moving within the stand and provides a point of reference for the thinning operation. No additional costs are associated with these trails in the planning model (*i.e.* the costs are considered part of the pre-commercial thinning operation).

3.8 PRODUCTIVITY AND COST ESTIMATE DATA

An estimate of the operating cost per hour is calculated and used as part of the pre-commercial thinning costs. Equipment can be grouped to provide cost estimates of operating combined systems of thinning. For example, the cost of motor-manual thinning, mechanical thinning and combined motor-manual-mechanical thinning can be estimated for a planning area. The information for the system costing models in this study is summarized in Appendix IV.

Pre-commercial thinning cost and productivity estimates are stored in ASCII text files for use by the DSS. These files include the system costing models, and the pre-commercial thinning productivity estimates. Pre-commercial thinning cost estimates can be obtained by multiplying the estimated system cost ($/PMH) with the estimated system productivity (ha/PMH). Cost estimates are calculated in the pre-commercial thinning planning model for each density class occurring in the planning area. Estimated total costs of pre-commercial thinning are presented in Figure 3.11 for a range of initial stand densities. The graph shows three pre-commercial thinning systems (chainsaw, brushsaw and mechanical).

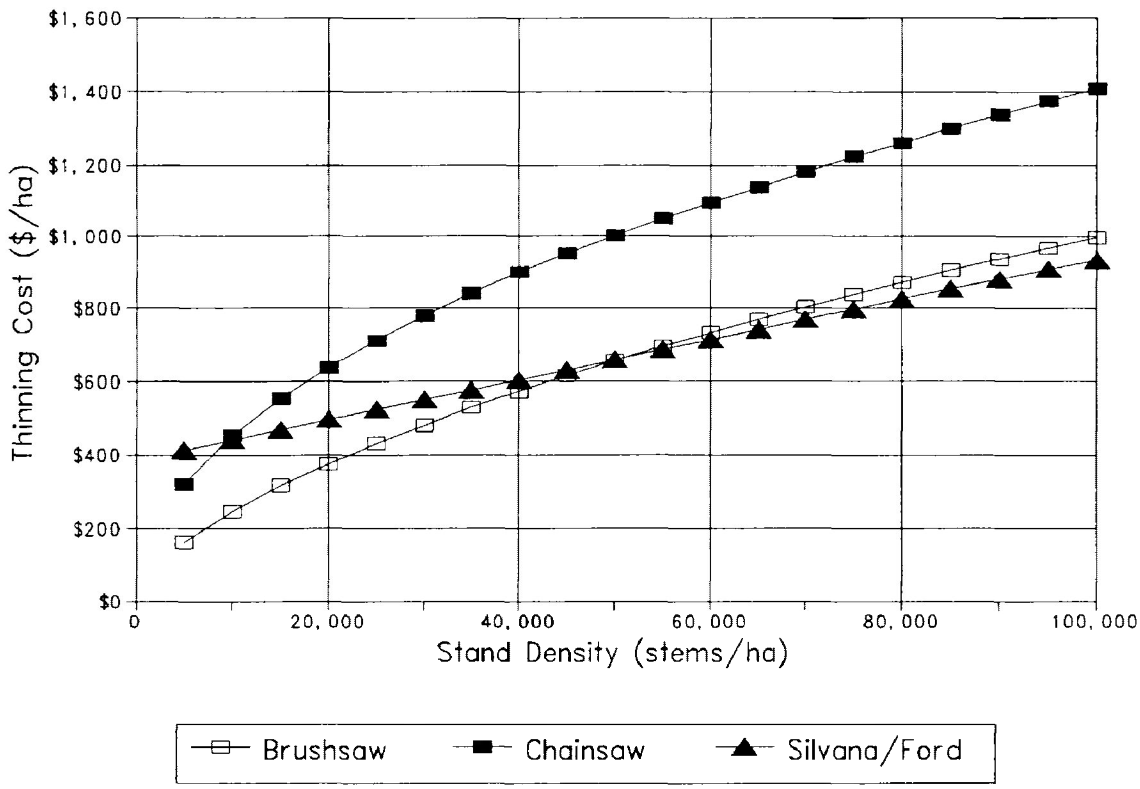


Figure 3.11 Pre-commercial thinning cost estimates ($/ha) for the brushsaw, chainsaw and the mechanical and motor-manual (Silvana/Ford and brushsaw) combination calculated from productivity (ha/PMH) (NSDNR, 1992; St-Amour and Ryans, 1992) and system cost models ($/PMH) (Rickard and Savage, 1983).

3.9 SENSITIVITY ANALYSIS OF THE PLANNING MODEL

Output from the model can be affected by variations in the data (*i.e.* stand density, operational costs, operational productivity). An essential portion of this study was to determine how the pre-commercial thinning DSS behaves under different circumstances and to compare the planning results to those of a systematic pre-commercial thinning layout. Parameters investigated include the resolution of the density stratification, variations in operational productivity and variations in allowable off-trail access distances.

Stand densities can be estimated at different resolutions within the forest (Figure 3.12). Density can be stratified on a stand-level basis (average stand density), on a compartment basis within a stand (strata within a stand), on a plot neighbourhood basis (nearest neighbour), or on a grid cell basis (interpolated density). Pre-commercial thinning planning results were compared to determine the effect of density stratification on the estimated pre-commercial thinning costs by comparing between stand-level, within-stand, nearest neighbour and interpolated cell densities.

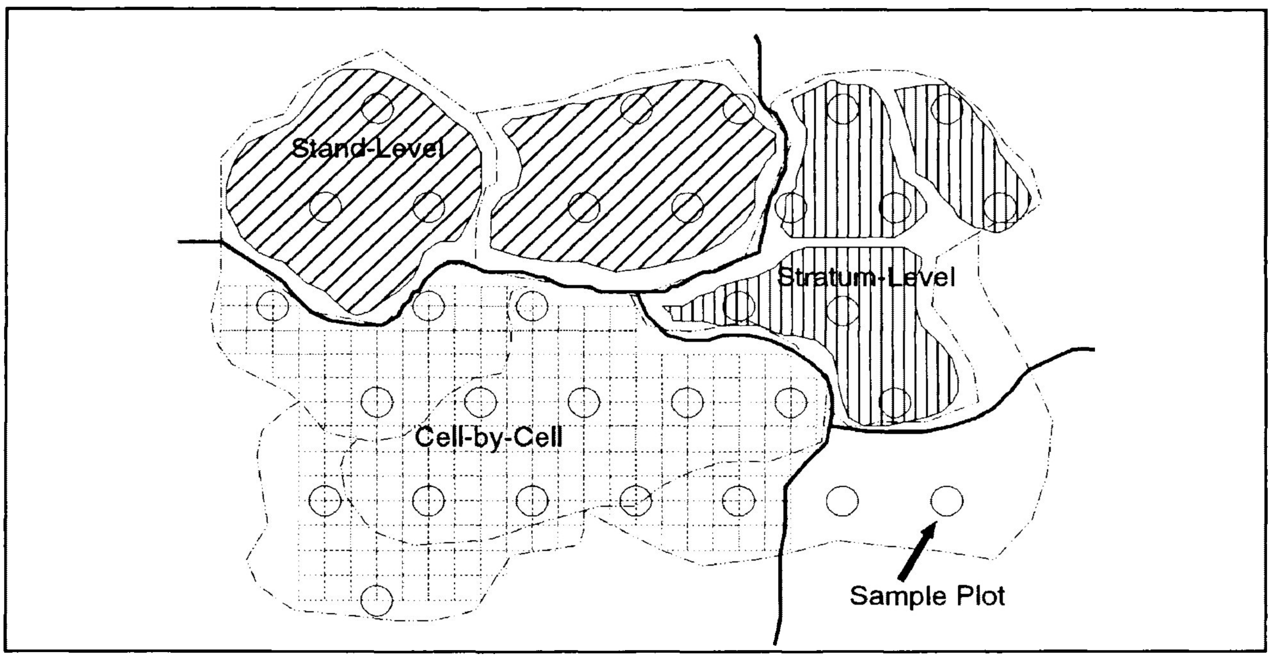


Figure 3.12 Stand-level, stratum-level and cell-by-cell density stratification for creating density maps for analysis with the pre-commercial thinning DSS.

A concern that the planner may have is the reliability of the data being used to estimate the costs of thinning. This concern is quite valid for the operational productivity (ha/PMH) estimates obtained from the literature. The regression coefficients for productivity based on initial stand density were poor ($r^2 < 0.5$). Therefore, it is important to determine how influential the productivity estimates are on the planning results. Productivity was varied in 10% increments ranging from 80% to 120% of the defined values to determine the sensitivity for the different pre-commercial thinning systems.

Another factor tested was the effect of changing the maximum allowable distance that pre-commercial thinning can be allocated from an access road. The off-trail access distance describes this maximum distance from a road/trail to be considered as accessible for thinning. The distance applied can describe the optimum off-trail distance for operation of a piece of equipment (*e.g.* optimum skidding distance in harvesting) or, in the case of thinning, the maximum distance a brushsaw operator wishes to be from fuel and maintenance tools during daily operations.

4 RESULTS

4.1 CASE STUDY RESULTS

The systematic sampling at Raith and at Martin provided stem density estimates for use with the pre-commercial thinning DSS. Three stands at Raith were sampled, and five stands at Martin. Table 4.1 summarizes the field data collected at the Raith and Martin study sites.

Table 4.1 Field data summary for the Raith and Martin study sites.

STAND	Number of plots	STEMS PER HECTARE Minimum	Maximum	Average	Std. Deviation
RAITH					
350	57	0	7,598	2,196	1,657
351	18	0	4,599	2,533	1,150
376	40	0	4,999	2,104	1,047
MARTIN					
218	85	0	20,594	8,953	4,889
223	104	0	16,795	7,411	3,719
227	21	400	9,997	2,714	2,326
228	22	0	8,398	2,572	2,243
249	248	0	22,394	6,325	3,242

These plot data were used to determine the stem densities within the case study stand density maps. Table 4.2 summarizes the density grid maps created from the field data. The cell value frequency distributions for each image generated are presented in

Appendix V. Generating these images on a 486/33 personal computer required approximately 1 minute for the baseline data (10,000 grid cells), 5 minutes for the Raith data (22,422 grid cells), and 10 hours for the Martin data (508,130 grid cells).

Table 4.2 Summary of density grid map files used for analysis.

IMAGE NAME	Image Size (pixels)	Image Resolution (cell size)	Average Density (stems/ha)	Std. Dev.	Minimum Density (stems/ha)	Maximum Density (stems/ha)
DEVELOPMENTAL DATA						
Baseline-1	100 x 100	10m x 10m	2 754	3 593	1 000	54 000
Baseline-2	100 x 100	10m x 10m	3 044	3 739	1 000	49 000
Baseline-3	100 x 100	10m x 10m	3 761	5 011	1 000	98 000
RAITH CASE STUDY DATA						
CIR photo	226 x 108	10m x 10m	2 338	511	600	3 600
Nearest Neighbour	223 x 102	10m x 10m	2 810	1 433	400	8 000
Interpolated	222 x 101	10m x 10m	2 658	975	400	8 000
MARTIN CASE STUDY DATA						
Interpolated	833 x 610	10m x 10m	6 573	2886	400	22 800

The image files can be described as follows:

1) Baseline grid map: created from the stem mapping data and used only in the developmental stages of the planning model to test and modify its performance.

2) CIR photo grid map: created from stand strata boundaries interpreted from colour infrared (CIR) photography; density values are based on the average plot values within each stratum.

3) Nearest-neighbour grid map: created from the forest stand boundaries; densities are based on field survey data, with cell values assigned the density value of the nearest field plot.

4) Interpolated grid map: created from the forest stand boundaries; densities are based on field survey data, with cell values interpolated between neighbouring plot locations using the inverse squared distance weighting technique.

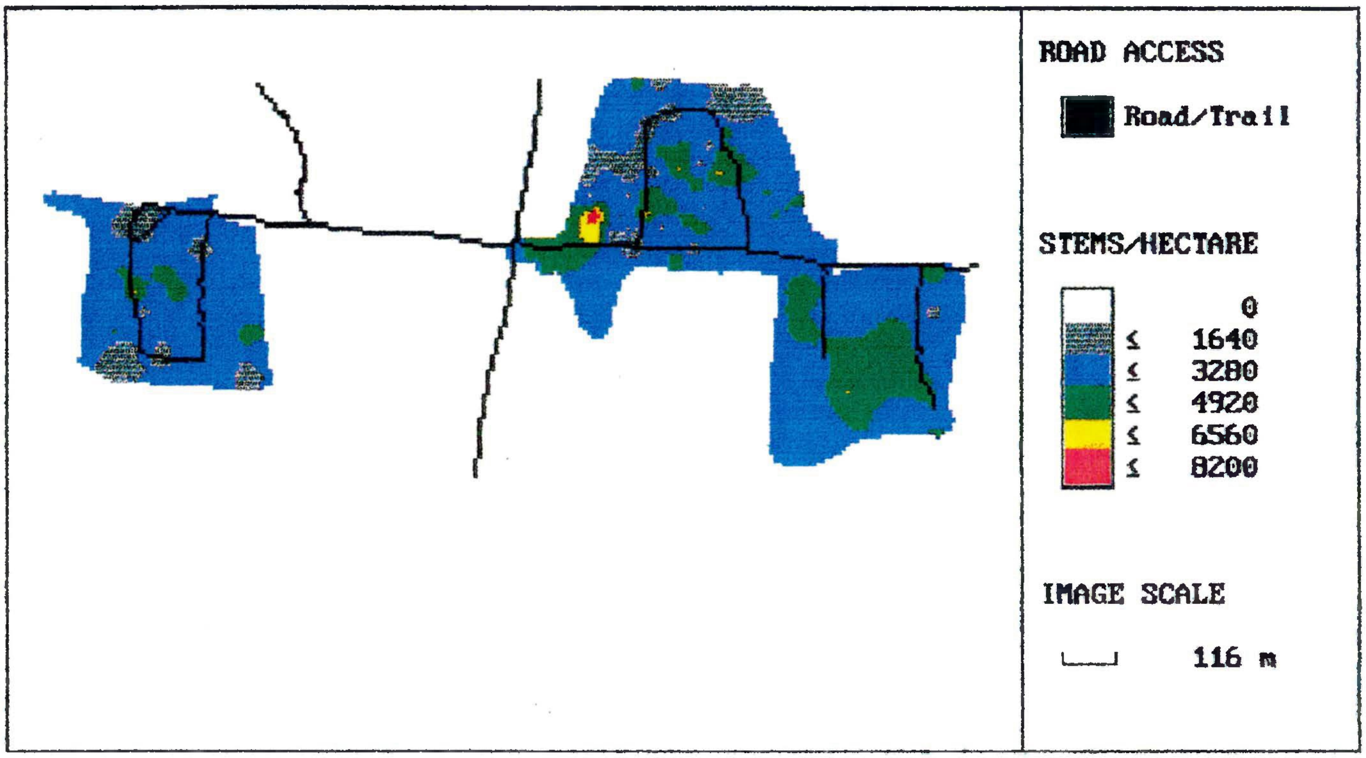
The original stand access maps provided the initial access into the stands. Each analysis by the planning model created an additional network of access trails into the allocated regions of the study area. These new access routes were connected to the existing network using a minimal spanning tree, thereby providing a minimum total distance of travel to allocated regions. Thinning was allocated around these trails within a buffer zone defined by the maximum off-trail distance for that trail type. All cells within this buffer distance are included in the productivity and cost estimates. An example of the initial access and the new access is presented in Figure 4.1 showing the Raith interpolated density map as the basis. The initial access and planned access for the Martin interpolated density map is presented in Figure 4.2. For the Martin study area the allocated nodes were spaced at equal intervals. With equal node distances, the minimal spanning tree will arbitrarily select the most recent node in the list. In this circumstance, the nodes were connected first along the lower limits of the stand.

The new trails consist of thinned swaths to provide easier access to areas requiring treatment within the stand and to provide a point of reference for the thinning operations within the stand. For the example in Figure 4.1 the average off-trail distance to access all points in the stand was reduced from 60 m in the initial access to 41 m in the new access, with a maximum distance of 280 m being reduced to 210 m, respectively. For the Raith interpolated image a total of 150 cells (1.5 km) representing access trails were added to the road/trail network, and a total of 3,875 cells (38.75 km) were added to the Martin network.

Simulations were performed for two motor-manual methods (chainsaw and brushsaw) and one mechanical selective method (Silvana Selective/Ford Versatile). All were applied to the same study area and with the same planning parameters. The system costing model provided the hourly operating costs for each system. The chainsaw was estimated to cost $29.85/PMH for pre-commercial thinning, the brushsaw to cost $30.64/PMH, and the Silvana Selective/Ford Versatile to cost $67.91/PMH. These costs describe the operating of the equipment and do not include contractor profits, administrative overhead costs, equipment transportation charges, or supervision costs.

The pre-commercial thinning productivity estimates were defined for 1,000 stems/ha density classes. Productivities for the interpolated density image are presented in Table 4.3.

The planning model used system operation costs ($/PMH) and productivity estimates (ha/PMH) to compute cost estimates of pre-commercial thinning for the study area. The cost estimates for the three pre-commercial thinning systems in the Raith and the Martin interpolated density images are presented in Table 4.4 with a comparison of "blanket" allocation and planned allocation.



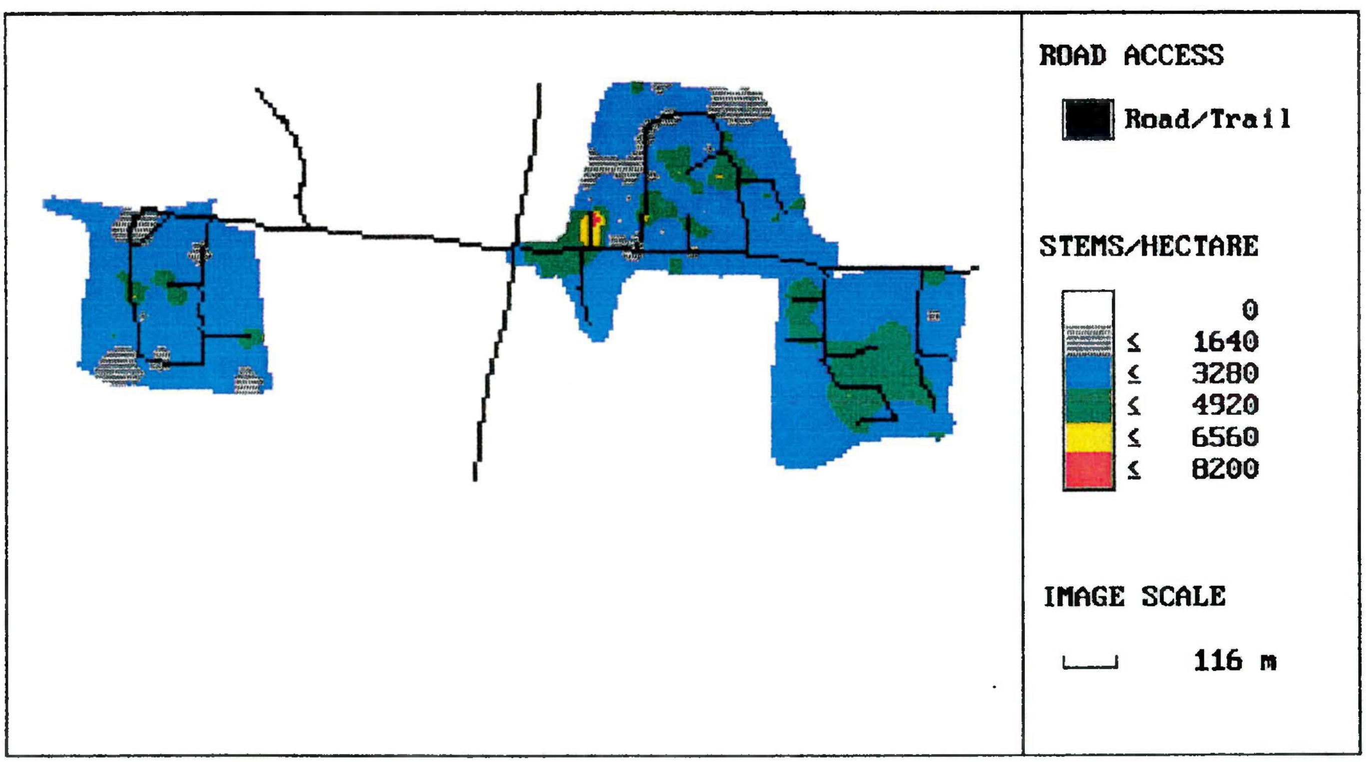
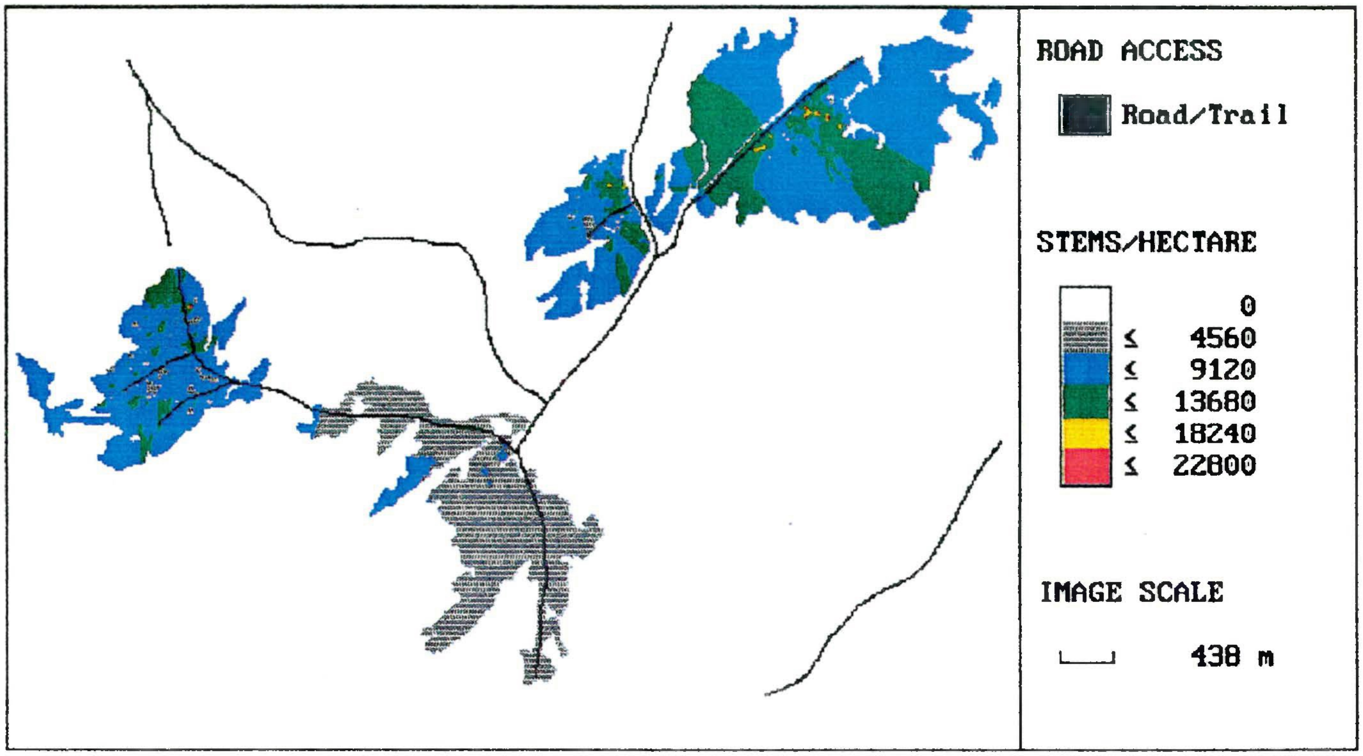


Figure 4.1 Raith jack pine blocks (stands 350, 351, and 376) showing the initial access trails (top) and the planned access trails (bottom).



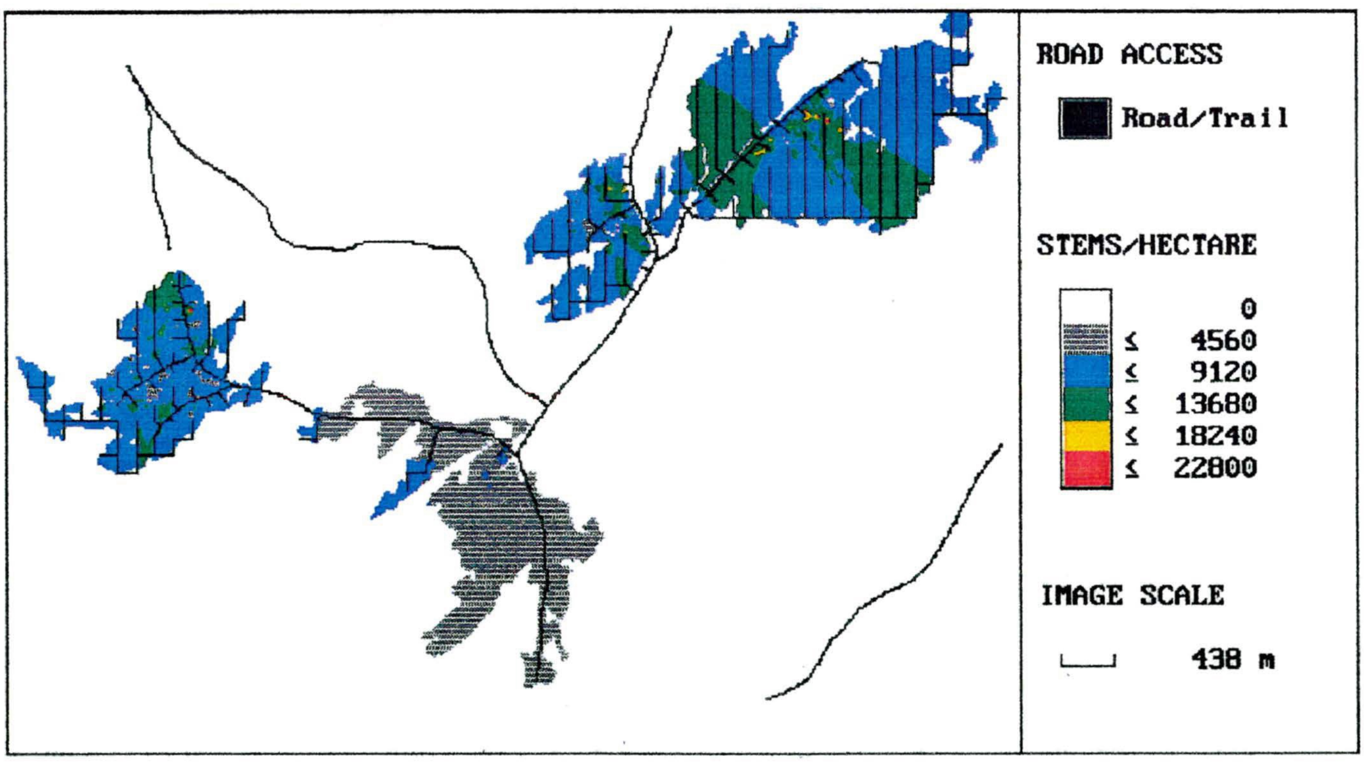


Figure 4.2 Martin jack pine blocks showing the initial access trails (top) and the planned access trails (bottom).

Table 4.3 Pre-commercial thinning productivity ranges for the chainsaw, brushsaw, and Silvana/Ford systems as estimated by the planning model.

DENSITY (stems/ha)	PRODUCTIVITY (ha/PMH) Chainsaw	Brushsaw	Silvana/Ford
0	0.000	0.000	0.000
1 000	0.205	0.497	0.296
2 000	0.146	0.327	0.289
3 000	0.119	0.256	0.283
4 000	0.103	0.215	0.276
5 000	0.093	0.188	0.270
6 000	0.085	0.168	0.265
7 000	0.079	0.153	0.259
8 000	0.074	0.141	0.254
9 000	0.069	0.132	0.249
10 000	0.066	0.124	0.244
11 000	0.063	0.117	0.239
12 000	0.060	0.111	0.235
13 000	0.058	0.105	0.230
14 000	0.056	0.101	0.226
15 000	0.054	0.097	0.222
16 000	0.052	0.093	0.218
17 000	0.051	0.090	0.214
18 000	0.049	0.087	0.211
19 000	0.048	0.084	0.207
20 000	0.047	0.081	0.204
21 000	0.046	0.079	0.200
22 000	0.045	0.077	0.197

Table 4.4 Pre-commercial thinning cost estimates for the chainsaw, brushsaw, and Silvana/Ford systems comparing total area treatment (unplanned) with planned treatment.

Study Area	Thinned Area (ha)	PRE-COMMERCIAL THINNING COST ESTIMATES Chainsaw ($)	($/ha)	Brushsaw ($)	($/ha)	Silvana/Ford ($)	($/ha)
RAITH INTERPOLATED							
Unplanned	64.02	13,190.01	206.03	6,072.61	94.85	15,070.86	235.41
Planned	46.11	9,802.17	212.58	4,542.86	98.52	10,887.44	236.12
MARTIN INTERPOLATED							
Unplanned	722.58	243,002.57	336.30	126,118.46	174.54	185,147.70	256.23
Planned	570.63	209,400.90	366.96	110,314.30	193.32	149,021.10	261.15

According to the planning model, the brushsaw is the cheapest pre-commercial thinning option for both the "blanket" allocation and the planned allocation. The chainsaw is the second best option for the Raith study area, and the Silvana/Ford is the second option for the Martin site. However, with a reduction of lower density areas allocated to thinning, the cost per hectare increased for all treatment options for the planned allocations. This is caused by a larger proportion of high density area in the allocated area; higher density areas have lower productivity rates, and therefore are more expensive to treat. Cost estimates by density class are described in Appendix VI for the Raith and the Martin case studies. These costs do not indicate the additional costs of supervision, transportation, and other overhead charges.

In all cases the planned allocation resulted in a reduction in total cost of pre-commercial thinning. The brushsaw showed a 25% reduction for the Raith study area and a 12% reduction for the Martin study area. The Silvana/Ford showed a 28% and a 19% reduction, respectively, and the chainsaw showed a 26% and a 14% reduction.

The thinned area for the Raith study site was reduced from 64 ha to 46 ha (-28%), and for the Martin study site the area was reduced from 723 ha to 571 ha (-21%).

4.2 COST OF PLANNING

Part of the total cost of planning is the cost of obtaining the required data (field surveys, aerial photography, and/or satellite imagery). Aerial CIR photography costs approximately $0.09/ha to acquire and another $0.03/ha to interpret for a total cost of $0.12/ha. Panchromatic SPOT satellite imagery costs approximately $2600 for a 60 km x 60 km image, or approximately $0.007/ha to acquire. Collection of the field data was estimated to cost $6.30/ha. The costs of obtaining the data for Raith and Martin are summarized in Table 4.5.

Table 4.5 Summary of costs of acquiring field data and CIR aerial photography for the Raith and Martin study sites.

Study Area	Cost ($/ha)	Total Area (ha)	Total Cost ($)
RAITH			
Field data	6.30	64.02	403.33
CIR photography	0.12	64.02	7.68
SPOT Panchromatic	0.007	64.02	0.44
MARTIN			
Field data	6.30	722.58	4552.25
CIR photography	0.12	722.58	86.71
SPOT Panchromatic	0.007	722.58	5.06

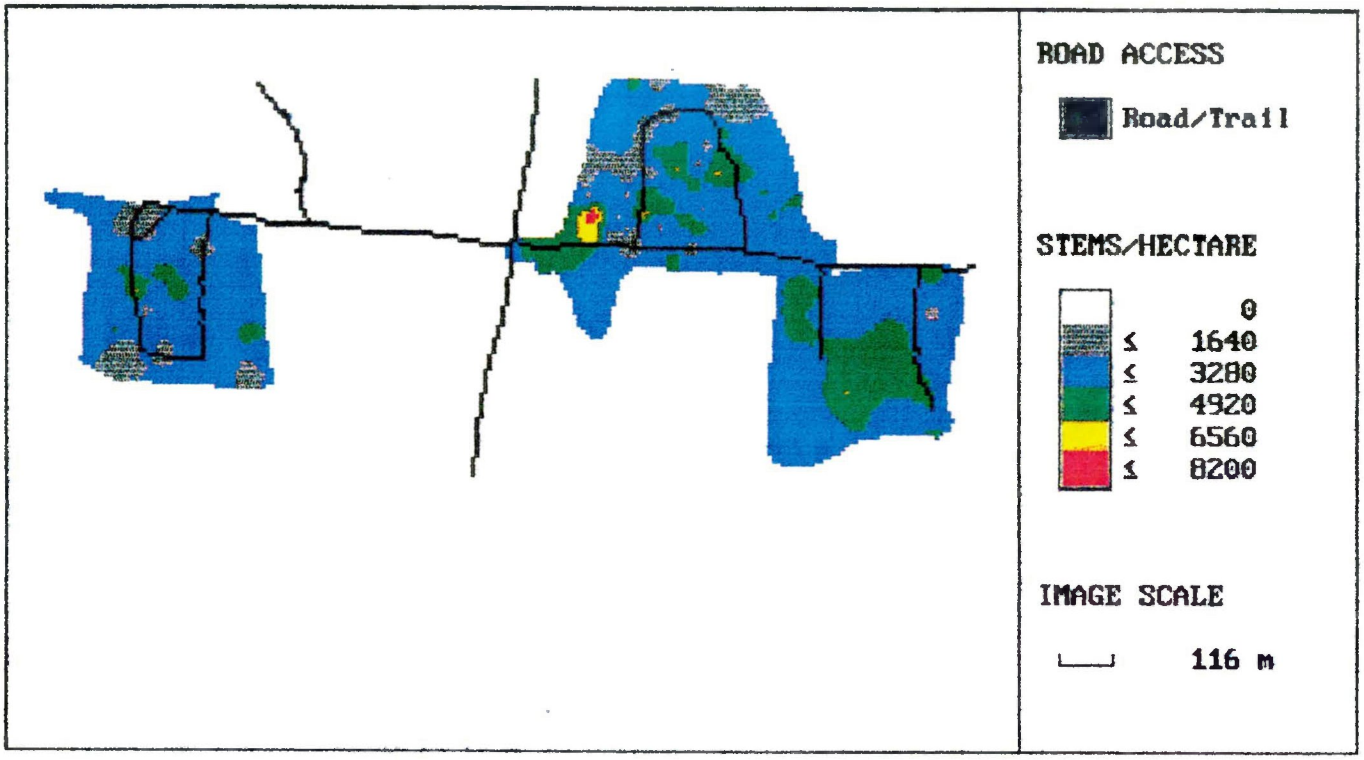
4.3 PLANNING MODEL SENSITIVITY ANALYSIS

To test the robustness of the pre-commercial thinning DSS, different data sets produced from different density sources and system costs were analysed. Analyses included:

1) using the nearest-neighbour density image and the CIR photograph density image to test the model's applicability to different levels of "clumpiness" in the data and to determine for which situations the model is most suitable,

2) cost estimates based on the three different pre-commercial thinning systems of two motor-manual (brushsaw and chainsaw) and a mechanical selective thinning (Silvana Selective/Ford Versatile spacing machine).

Figures 4.3 to 4.5 present the initial density image and the proposed area of treatment from the new access trails. The CIR imagery had an additional 32 cells (320 m) marked for new trails, the nearest-neighbour imagery had 163 cells (1.6 km) of trails. Notice that for all cases there are regions (white patches) within the stands that did not contain sufficient density to be considered as eligible for pre-commercial thinning. Table 4.6 summarizes the cost estimates based on brushsaw pre-commercial thinning of the entire images (*i.e.* "blanket" thinning). Table 4.7 presents the cost estimates for the proposed treatment allocations for the same images (*i.e.* "planned" thinning). Notice that the untreated areas may contain small patches (less than the defined minimum node area) of eligible density that were not large enough to be included in the allocation. Similarly, the inclusion of 1000 and 2000 stems/ha in the treated area is caused by small patches being interspersed throughout the allocated pre-commercial thinning corridors.



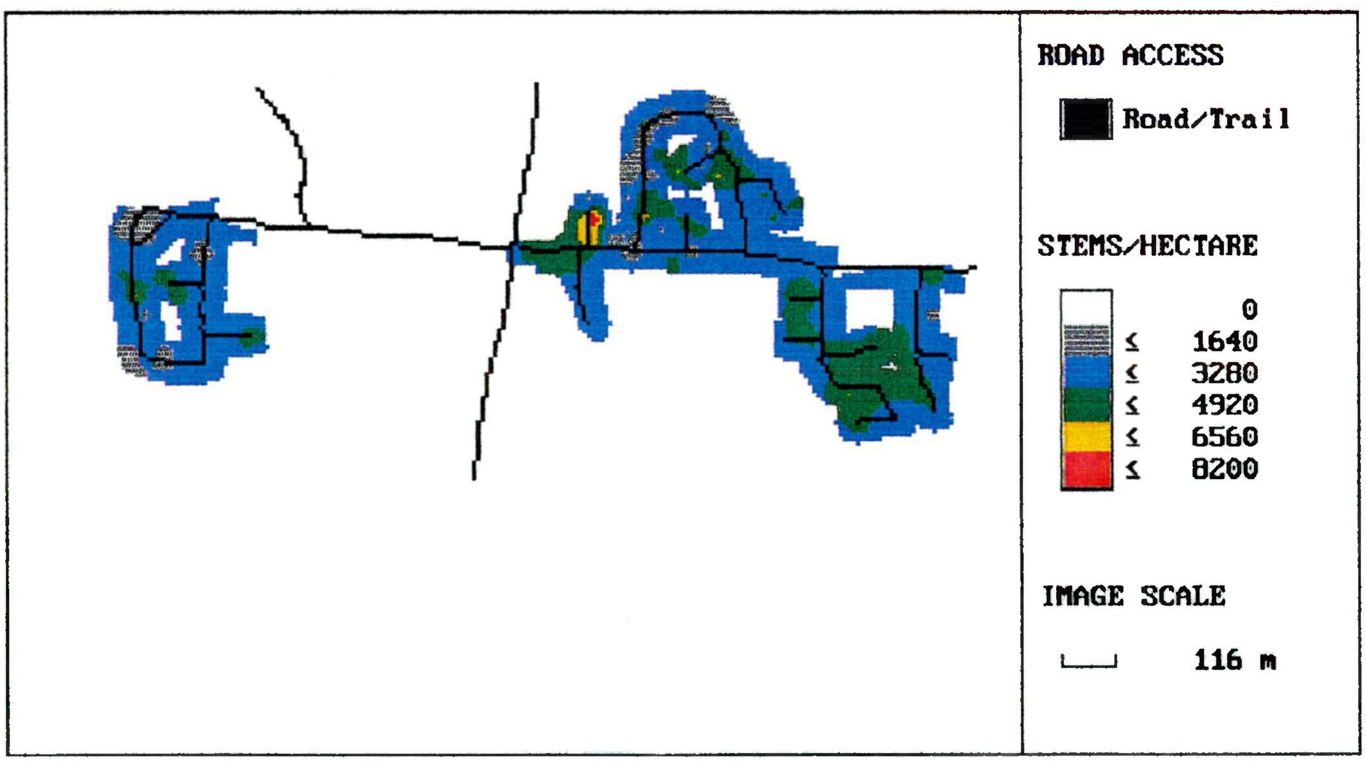


Figure 4.3 Raith interpolated density images before (top) and after (bottom) proposed treatment allocation, showing the new access routes and accessible areas.

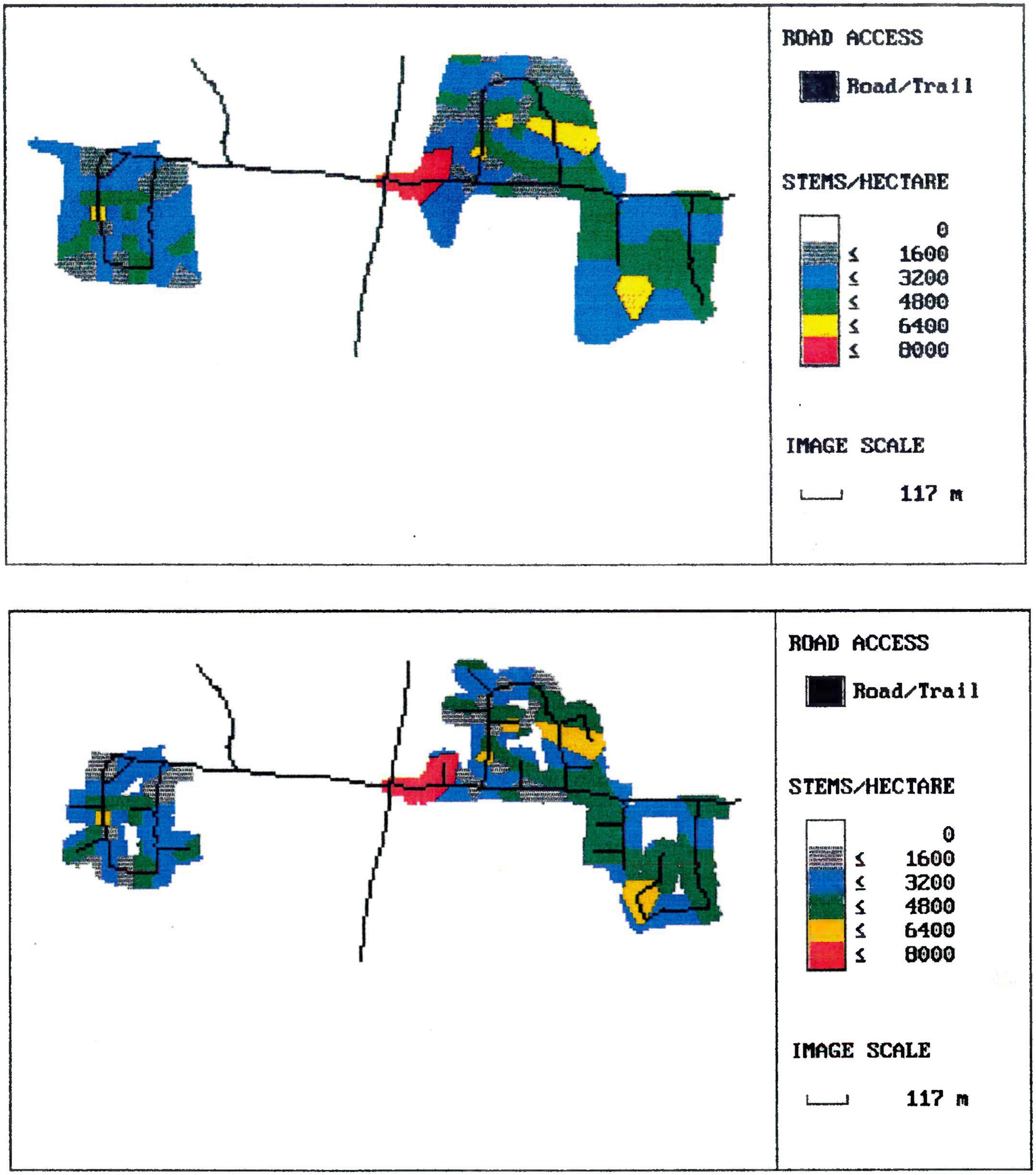


Figure 4.4 Raith nearest-neighbour density images before (top) and after (bottom) treatment allocation, showing the new access routes and accessible area.

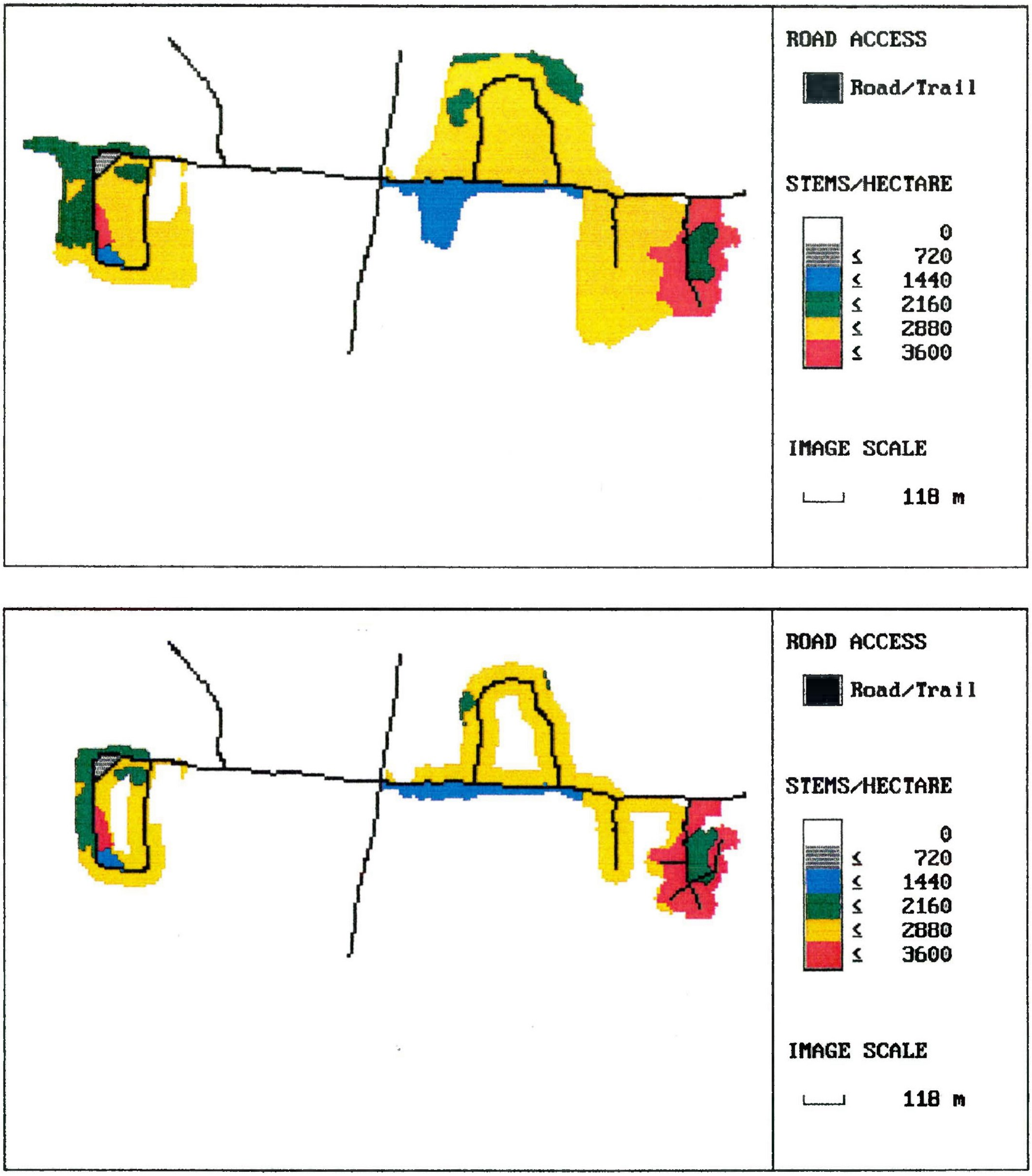


Figure 4.5 Raith CIR photography density images before (top) and after (bottom) treatment allocation, showing the new access routes and accessible area.

Table 4.6 Pre-commercial thinning cost estimates for "blanket" allocation of brushsaw pre-commercial thinning to the entire interpolated, nearest neighbour, and CIR photography density images for the Raith study area.

DENSITY	BRUSHSAW PRE-COMMERCIAL THINNING COST ESTIMATES					
	Interpolated		Nearest Neighbour		CIR Photography	
(stems/ha)	(ha)	($)	(ha)	($)	(ha)	($)
1000	14.37	886.06	14.17	873.73	13.00	801.59
2000	31.13	2,917.41	18.10	1,696.27	42.81	4,011.83
3000	16.73	2,002.72	15.26	1,826.75	2.25	628.46
4000	1.36	193.85	4.98	709.82	0.00	0.00
5000	0.33	53.79	2.36	384.69	0.00	0.00
6000	0.07	12.77	1.85	337.46	0.00	0.00
7000	0.03	6.01	0.45	90.13	0.00	0.00
TOTAL	64.02	6,072.61	57.17	5,918.85	58.06	5,441.88

Table 4.7 Pre-commercial thinning cost estimates for the planned allocation of brushsaw pre-commercial thinning to the interpolated, nearest neighbour, and CIR photography density images for the Raith study area.

DENSITY	BRUSHSAW PRE-COMMERCIAL THINNING COST ESTIMATES					
	Interpolated		Nearest Neighbour		CIR Photography	
(stems/ha)	(ha)	($)	(ha)	($)	(ha)	($)
Untreated	17.91	0.00	13.66	0.00	23.37	0.00
1000	9.09	560.49	9.20	567.28	7.02	432.85
2000	19.29	1,807.80	10.64	997.14	22.83	2139.55
3000	15.94	1,908.15	14.31	1,713.03	4.84	579.38
4000	1.36	193.85	4.83	688.44	0.00	0.00
5000	0.33	53.79	2.29	373.28	0.00	0.00
6000	0.07	12.77	1.80	328.34	0.00	0.00
7000	0.03	6.01	0.44	88.13	0.00	0.00
Sub-Total	46.11		57.17		34.69	
TOTAL	64.02	4,542.85	57.17	4,755.63	58.06	3,151.79

As with the previous analyses, the planned pre-commercial thinning allocations are estimated to be cheaper than performing a "blanket" allocation. Changes in total cost estimates showed a $1,529.76 reduction (-25%) for the interpolated density image, a $1,163.22 reduction (-20%) for the nearest neighbour density image, and $2,290.09 reduction (-42%) for the CIR photography density image. These values indicate the cost of the thinning operation within the treated stands and do not account for the cost of supervision, transportation and overhead charges.

Similar to the result with the different pre-commercial thinning systems, the planned allocation also showed changes in the area treated. The treated area for the interpolated image decreased by 28%, the nearest neighbour image decreased by 24%, and the CIR image by 40%.

The associated costs per hectare also change from image to image. The interpolated image increased from $94.85/ha to $98.52/ha (4% increase), the nearest neighbour image from $103.53/ha to $109.30/ha (6% increase), and the CIR image decreased from $93.73/ha to $90.86/ha (3% decrease).

Variation in thinning productivity also shows wide ranges in cost estimates. The pre-commercial cost estimate using productivity at 80, 90, 100, 110, and 120 percent are presented graphically in Figure 4.6 for each density class. Lowering the productivity of one system at a time reveals a drastic change in the intercepts of the cheapest thinning option for a given density. Results of applying these pre-commercial thinning productivities to the planning analysis are given in Table 4.8.

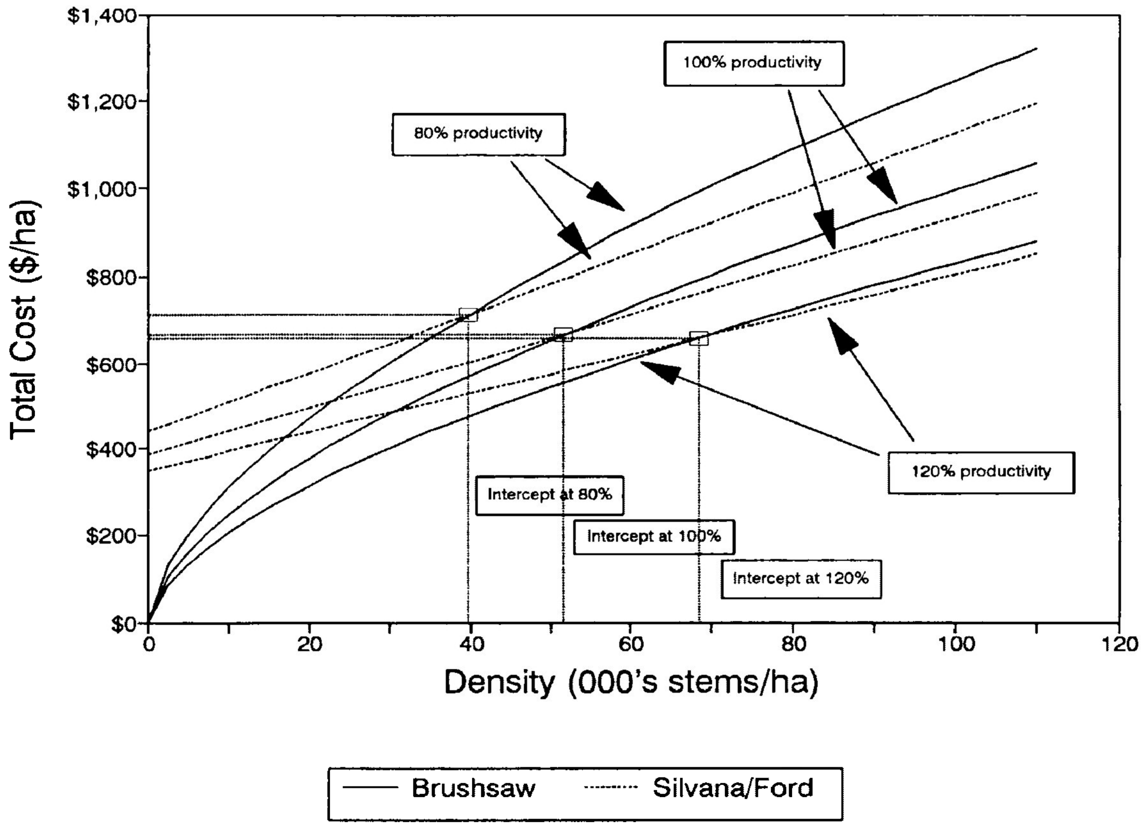


Figure 4.6 Pre-commercial thinning cost comparisons ($/ha) for the brushsaw and the Silvana Selective/Ford Versatile systems showing the cost intercepts at 80%, 100% and 120% productivity.

Table 4.8 Pre-commercial thinning cost estimates using a "blanket" allocation for productivity levels of 80, 90, 100, 110, and 120 percent for the Raith interpolated density image.

PRODUCTIVITY	PRE-COMMERCIAL THINNING COST ESTIMATES					
	Chainsaw		Brushsaw		Silvana/Ford	
(%)	($)	($/ha)	($)	($/ha)	($)	($/ha)
80	16,550.63	258.52	7,598.44	118.69	18,851.53	294.46
90	14,687.61	229.42	6,755.81	105.53	16,751.74	261.66
100	13,190.01	206.03	6,072.61	94.85	15,070.86	235.41
110	12,012.24	187.63	5,530.93	86.39	13,698.16	213.97
120	10,992.34	171.71	5,064.66	79.11	12,562.33	196.23

For variations in productivity levels, the brushsaw is the cheapest for the productivity range investigated. For the chainsaw and the Silvana/Ford, however, an increase of 10% productivity for the chainsaw, or a decrease of 10% productivity for the Silvana/Ford will make the chainsaw the cheaper of the two pre-commercial thinning systems.

There is also the question of the effect variations in allowable access distance from a trail into the stand will have on the cost estimates. Variations in the allowable off-trail access distances were investigated with allowable access distances of 20 metres, 50 metres (basic scenario), and 100 metres. The cost estimates are presented in Table 4.9 and their matching allocation maps are presented in Figure 4.7 to 4.9. The off-trail access distance represents the maximum distance a given cell can be from a trail in order to be allocated for pre-commercial thinning.

Table 4.9 Cost estimates ($) for 20-metre, 50-metre (basic scenario), and 100-metre off-trail access distances for the interpolated density image.

DENSITY	COST ESTIMATES ($) FOR CHANGES IN ACCESS DISTANCES					
	20-m Access		50-m Access (Base Scenario)		100-m Access	
(stems/ha)	(ha)	($)	(ha)	($)	(ha)	($)
Untreated	47.84	0.00	17.91	0.00	6.28	0.00
1000	4.83	297.82	9.09	560.49	12.27	756.57
2000	6.61	619.46	19.29	1,807.80	27.15	2,544.41
3000	4.21	503.96	15.94	1,908.15	16.53	1,978.78
4000	0.40	57.01	1.36	193.85	1.36	193.85
5000	0.12	19.56	0.33	53.79	0.33	53.79
6000	0.01	1.82	0.07	12.77	0.07	12.77
7000	0.00	0.00	0.03	6.01	0.03	6.01
Sub-Total	16.18		46.11		57.74	
TOTAL	64.02	1,499.64	64.02	4,542.85	64.02	5,546.18

Table 4.10 Comparison of 50-metre off-trail access (base scenario) with 100-metre off-trail access for pre-commercial thinning in the interpolated density map.

	MAXIMUM ALLOWABLE OFF-TRAIL DISTANCE	
	50 m	100 m
Area Treated (ha)	46.11	57.74
Total Cost ($)	4542.85	5546.18
Cost per Hectare ($/ha)	98.52	96.05
Average Distance (m)	40.7	49.5
Maximum Distance (m)	210.0	230.0
Length of New Trails (m)	1500.0	580.0

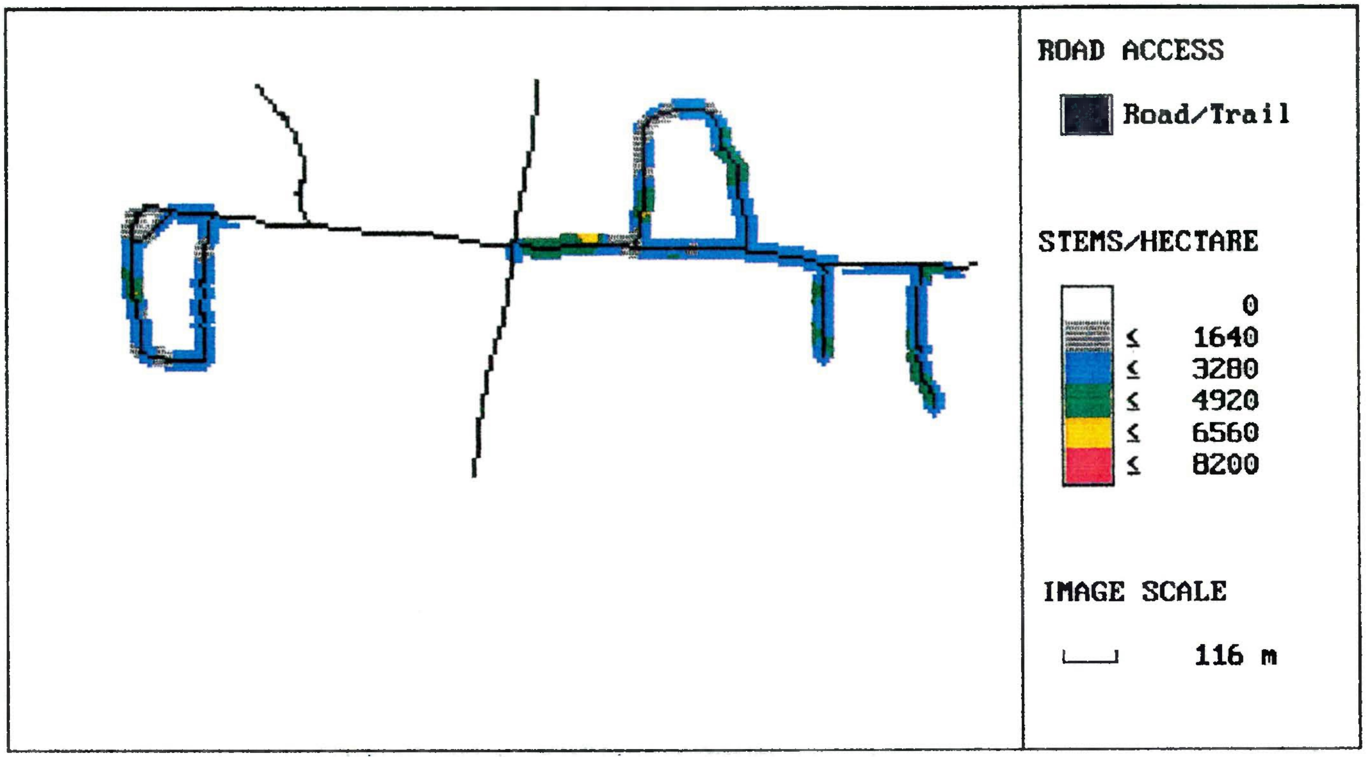


Figure 4.7 Treatment allocations in the interpolated density image using an allowable off-trail access distance of 20 metres.

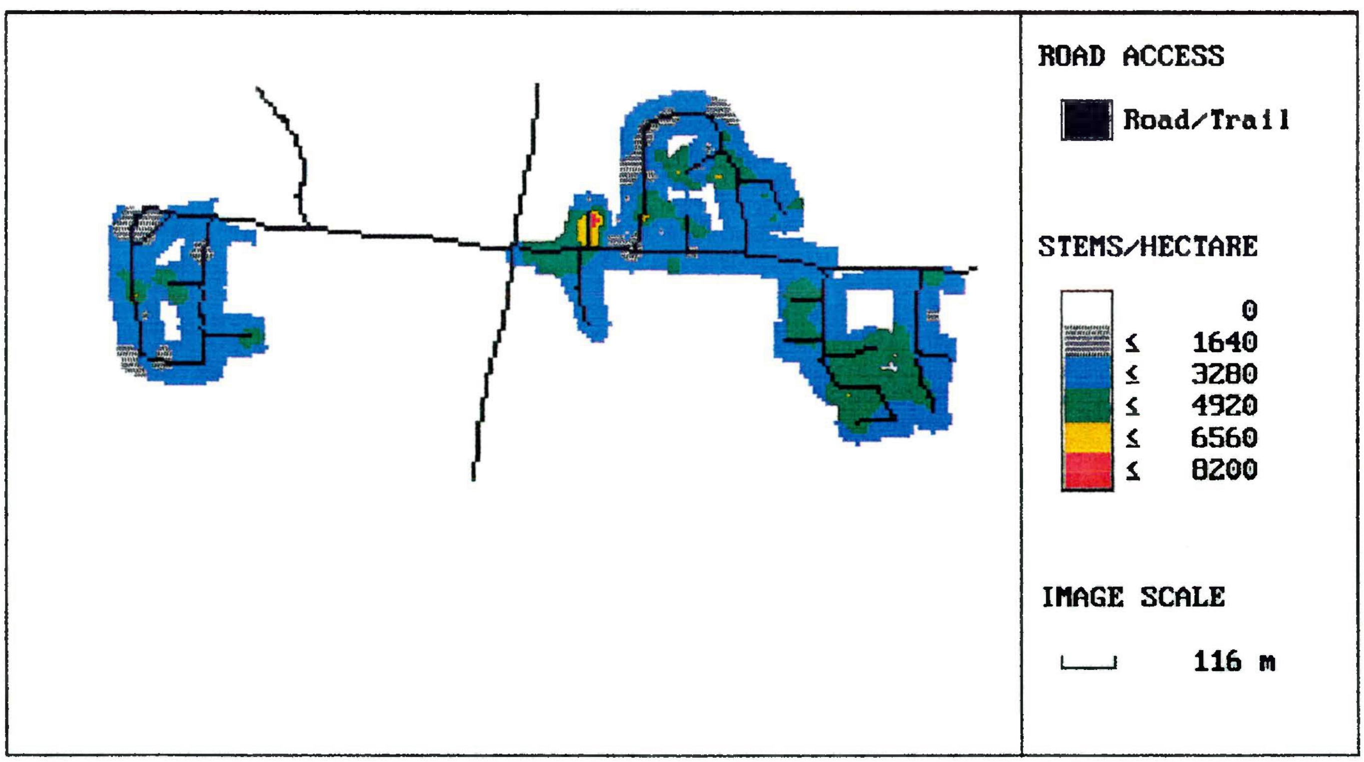


Figure 4.8 Treatment allocations in the interpolated density image using an allowable off-trail access distance of 50 metres (basic scenario).

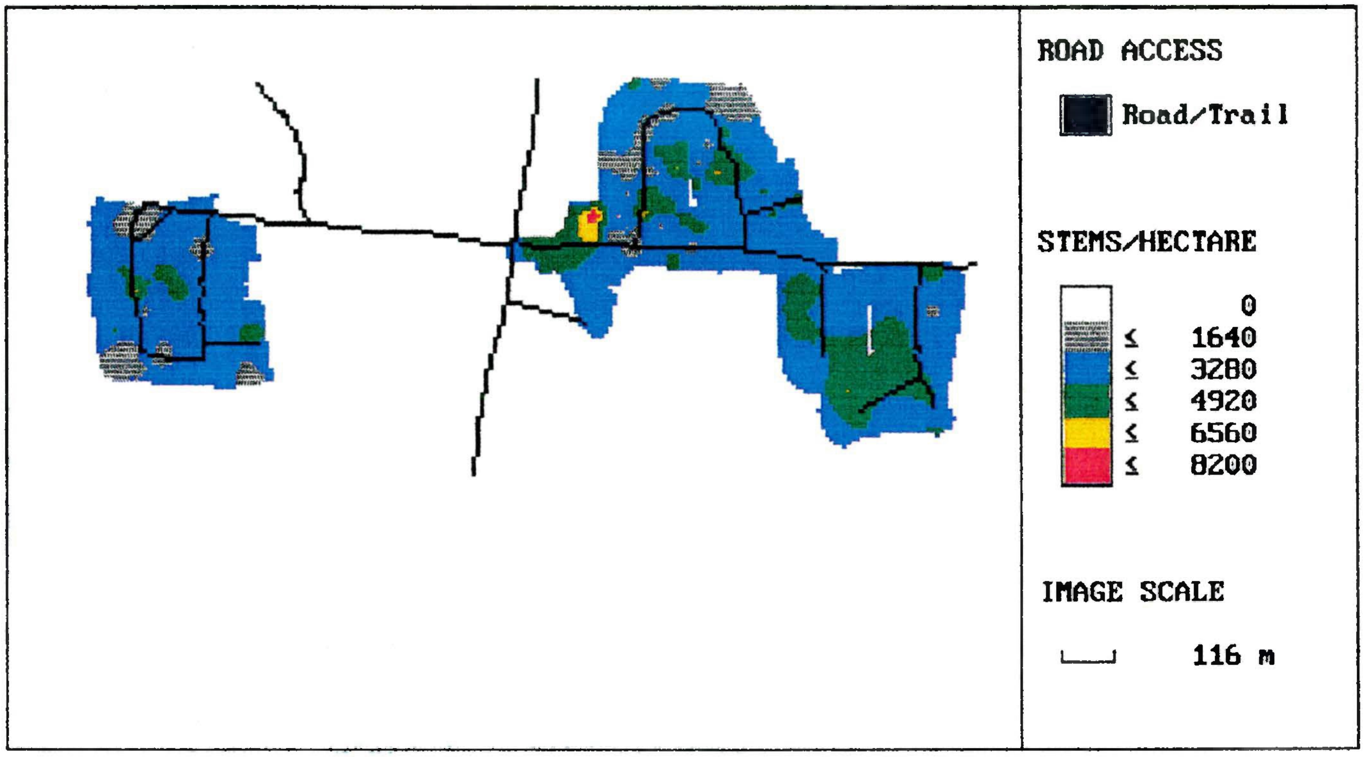


Figure 4.9 Treatment allocations in the interpolated density image using an allowable off-trail access distance of 100 metres.

5 DISCUSSION

The analyses using the pre-commercial thinning DSS showed both strengths and weaknesses. Data quality is a very important factor affecting the results of the model's analysis. The data must be inexpensive, detailed and accurate in order for the pre-commercial thinning model to provide useful results.

The intent of the theoretical data was to provide a method for analyzing large tracts of land for density and spacing treatment allocation. If the study site data (satellite imagery and field data) had been used to develop the model then there is the problem of the frame of reference (validity of the model for other populations). Theoretical data provided a training ground for testing the model's validity and sensitivity. It also provided a subset of data for debugging and estimating the model's efficiency (time to run, storage space required).

5.1 CASE STUDY

Actual case study data was required to test the applicability of the model to planning pre-commercial thinning for jack pine stands. The ARC/INFO vector maps provided the general stand boundaries but did not give any detail of the internal structure of each stand. This detail was obtained from field data and from aerial photography. The time required on a 486/33 personal computer to interpolate the density values was dependent on the image size; the stand density maps for Raith required 5 minutes to generate (115 field plots across 22,422 cells) and the Martin data required 10 hours to generate (480 field plots across 508,130 cells).

The systematic field surveys gave a good description of the stem density across the entire stand. However, they did not account for the level of sampling intensity that may be required (*i.e.* density variation may be low enough to require fewer plots to determine the density with 95% confidence). Operationally, preliminary field samples would determine the required sampling intensity, and additional plots would be sampled to satisfy the desired confidence interval.

Changes in stem density in the sampled stands could sometimes be very abrupt. Along road edges there was often a border of higher stem density approximately a metre wide, with lower densities further from the road. Also, for the Martin site, there sometimes occurred rows of high density parallel to the site preparation disc trenches, creating a distinctive regular pattern of density that would most likely affect pre-commercial thinning productivity. Spatial pattern of density in addition to initial stem density could be a possible factor in estimating pre-commercial thinning productivity.

Spatial resolution of the stem density estimates had an effect on the planning model results. The CIR resulted in the lowest total pre-commercial thinning cost after planning compared to the interpolated imagery and the nearest-neighbour imagery (the most expensive). The CIR imagery also had the lowest density and the lowest maximum density. Averaging of stem densities in the stand strata smoothed out any small high density pockets and resulted in a more uniform pattern of density. As a result, the planning model found fewer areas within the stands considered eligible for thinning.

Finer spatial resolutions gave a more detailed description of the stem densities within the stands and resulted in more clumped patterns of stem density. Both the nearest-neighbour grid maps and the interpolated grid maps showed transitions from high to low density across the stands. The interpolated density map tended to present a more gradual density transition and missed the sharp changes (*e.g.* road edges) observed in the field.

Increasing the spatial resolution to detect and represent these sharp variations in density would require more cells to describe the same area, and would require more computational effort. A balance between desired detail and acceptable analysis time needs to be achieved to maintain any cost savings created by using the planning model.

Using a 10-metre pixel resolution allowed sufficient detail for the description of the access road locations. A pixel resolution size larger than 10-metres would provide less detailed descriptions of the road locations and could in turn alter the network analysis results. A tremendous amount of computational time was required, however, to perform the network analysis for the 10-metre raster data. The Martin initial access roads consisted of 2,155 grid cells, and after the minimal spanning tree was completed, the new network had increased to 6,030 cells. The subsequent operations of allocating and costing the pre-commercial thinning along these trails consumed a large portion of the computational effort. One solution to reduce the required analysis time is to use a faster computer. If this is not a viable solution, then an alternative would be to reduce the number of cells representing the road locations. This could be done by retaining the road location description in a vector format, thereby reducing buffering operations to using the nodes along the vector. This, however, could introduce errors associated with using different spatial formats (*i.e.* raster and vector).

Although the model is quite sensitive to the size of the data sets during analysis, once an allocation is planned it is possible to test a variety of pre-commercial thinning systems on this area. The ability to investigate different pre-commercial thinning systems for the same treatment area provided a good method for selecting and comparing potential pre-commercial thinning options. Varying the costs of operating equipment and the productivity levels can address the questions of how the total cost of treating the area will be affected.

The system costing model does not, include contractor profit, administrative cost, supervisory cost, transportation cost or overhead cost. Rather, it simply describes operation of the equipment in the stand. Additional costs can be added as fixed costs associated with the pre-commercial thinning with a specific system to provide a total operational cost.

Productivity estimation by density provided a detailed breakdown of the cost of pre-commercial thinning. Although the model reports the thinning costs for density and hectares treated, it would also be good to determine where most of the cost is incurred. Inspection of Table 5.1 suggests the level of effort is focused away from the densities below 3,000 stems/ha (the minimum eligible density for this study). Table 5.1 summarizes the proportion of costs applied to each density class for pre-commercial thinning with a brushsaw. The cost reductions occur mainly in the 1,000 and 2,000 stems/ha density class with some reduction also occurring in the 3,000 stems/ha density class.

The low density areas allocated for pre-commercial thinning occurred within the accessible off-trail distance along the proposed access trails. This is based on the assumption that the worker will enter all portions of the allocated block to ensure that the pre-commercial thinning achieves the target density. The proportion of area within a given node can be controlled by increasing or decreasing the minimum area of eligible density for a node to be considered for allocation. For the purposes of this study, this value was set at 0.25 ha (*i.e.* each node must contain a minimum of 0.25 ha with stem densities at or above the eligible density).

Table 5.1 Breakdown of the pre-commercial thinning with a brushsaw comparing total allocation and planned allocation.

DENSITY (stems/ha)	TOTAL AREA ALLOCATION Area (ha)	Cost ($)	(%)	PLANNING MODEL ALLOCATION Area (ha)	Cost ($)	(%)
1000	14.37	886.06	14.6%	9.09	560.49	12.3%
2000	31.13	2917.41	48.0%	19.29	1807.80	39.8%
3000	16.73	2002.72	33.0%	15.94	1908.15	42.0%
4000	1.63	193.85	3.2%	1.36	193.85	4.3%
5000	0.33	53.79	0.9%	0.33	53.79	1.2%
6000	0.07	12.77	0.2%	0.07	12.77	0.3%
7000	0.03	6.01	0.1%	0.03	6.01	0.1%
TOTAL	64.02	6072.61	100.00%	46.11	4542.86	100.00%

5.2 PLANNING MODEL SENSITIVITY ANALYSIS

Sensitivity analysis tested different density images containing varying spatial patterns of density, different levels of pre-commercial thinning productivity, and variations in accessible distance from roads and trails. Analyses showed that the model results are affected by changes in variability of density spatial patterns, variations in operational productivity, and variations in access distances.

The three images used (CIR photography, nearest-neighbour, and interpolated) showed some of the effect of aggregation of density in larger area classifications. For the CIR photography, the aggregations averaged out the high density pockets that occurred across the stands. This reduced the total area allocated for treatment and effectively omitted some high density pockets from being pre-commercially thinned. The total cost of pre-commercial thinning was reduced from $5,441.88 for the "blanket" allocation to $3,151.79 for the planned allocation (a 42% reduction). This image had the lowest average density (2,338 stems/ha) and lowest variability of the three images.

The nearest-neighbour described the presence of high density pockets, but did not account for the variation in density that can occur between plot locations. The cost of "blanket" allocation was estimated at $5,918.85 and was reduced to $4,755.63 for the planned allocation (a 20% reduction). This image had the highest average density (2,810 stems/ha) and the highest variability.

The inverse weighted distance (interpolation) method does, however, give a more detailed description of the high density pockets as well as representing the density gradient between plots. The cost estimate was $6,072.61 for the "blanket" allocation and

$4,542.85 for the planned allocation (a 25% reduction). This image's density (2,658 stems/ha) fell midway between the other two images, as did the variability.

Although the increased cost savings may be associated with a reduced density variation, it is more likely that stem density is the over-riding factor. If the CIR image was to have a slightly higher average density, enough to move the majority of the area into an eligible density class, then the pre-commercial thinning allocations would tend to cover more of the image. Eventually, as the average density increased, the allocated area would almost equal the "blanket" allocation. Investigating additional data sets containing spatial density patterns ranging from uniform to clumped patterns might give a better indication of the effects of density variation on the planning model's results. The model results seem to suggest that focusing the pre-commercial thinning in higher density areas will result in decreased total costs, but as the stand's average density approaches the minimum eligible density, the allocations will begin to resemble a "blanket" allocation, and result in lower cost savings.

Variations in operational productivity also create a difference in the cost estimates calculated by the planning model. The effect is most noticeable if the productivity of a specific system is over-estimated. For example, if the brushsaw productivity is reduced to 80% of the original estimate (a 20% reduction), the cost per hectare increases by 25% (*i.e.* $94.85/ha increases to $118.69/ha). On the other hand, an increase in productivity of 20% yields only a 17% reduction in cost per hectare (*i.e.* $94.85/ha reduces to $79.11/ha). This shows that productivity estimation needs to be improved to reduce the potentially large variations in cost estimates.

Other factors affecting pre-commercial thinning productivity need to be considered to improve confidence in the planned thinning cost estimates. Additional parameters such as tree species composition, tree height, spatial patterns of stem density, season of operation, and terrain conditions could all help to improve productivity estimates. Pre-commercial thinning productivity studies could include a detailed description of initial stand conditions (*e.g.* tree species, stem density, stem diameter, tree height, terrain and weather) and, using an experimental design, perform time studies with different workers in individual blocks. This data could provide a better basis for estimating productivity for different pre-commercial thinning methodologies.

Another trend observed was the effect the allowable off-trail distance had on the average and maximum distance from all points in the stand to the nearest road or trail. This table 4.10 shows that increasing the allowable off-trail access distance caused an increase in the average distance to roads and trails from the stand. It did, however, require approximately 60% fewer trails to allocate and treat the same stand with the 100 m access. Inspection of the resulting allocation maps (Figures 4.8 and 4.9) also shows that using the 50 m off-trail access distance results in a more complex arrangement of thinned areas. The cost of marking these areas for pre-commercial thinning in the field could quickly over-come any cost savings generated from using the lower access distance. In this case, selection of the larger access distance could be more beneficial for planning purposes.

5.3 COST ESTIMATION COMPARISON

In the case study areas, the total cost estimates were higher for the "blanket" allocations than for the planned allocations. Estimated reductions in costs for the Raith study area were $3387.84 (26% savings) for the chainsaw, $1529.75 (25% savings) for the brushsaw, and $4183.42 (28% savings) for the Silvana/Ford. These savings exceed the cost of field work ($403.33), aerial photography ($7.68), and satellite imagery ($0.44) by a large margin. This suggests that the investment in sampling the study area is a worthwhile cost for this study area.

5.4 ACCESS PLANNING

The method of allocating stand area using a node search for eligible density needs to be improved slightly. Some shortcomings of the method include:

1) the inclusion of ineligible density cells within the allocation radius from node-centre,

2) the "missing" of some areas or patches within an image that could create or could be caused by a bias in the model results, and

3) the lack of an estimation of a "shadow cost" indicating what additional resources (time and money) are required to allocate and access more of the image.

During the allocation phases of pre-commercial thinning, all cells within the buffer distance from road/trail access are included. Low density (ineligible) cells are likely to be present and will alter the cost estimates. These cells could be excluded from the allocation, but this would increase the complexity of applying the allocation in the field. The assumption was made that the worker will access all areas within the marked boundaries to ensure that the pre-commercial thinning target density is achieved. The report file does list the allocated cells by their density with subtotals of area and cost, so the manager/decision-maker can obtain some idea about what proportions of the allocation are actually occurring in low density areas. Altering the minimum eligible area parameter will reduce or increase the amount of low density cells allowed within a given node.

Missed patches in an allocation are not a serious difficulty. This can be corrected by simply increasing the allowed buffer distance from the relevant access routes. For example, if the allocation tends to leave a strip approximately 20 metres wide between two access routes, then the allowable buffer distance could simply be increased by another 10 or 15 metres to ensure enough overlap between adjacent access routes.

Although a "shadow cost" was not part of the initial design of the pre-commercial thinning DSS it is possible to compare the estimated costs of allocating the entire image, against the cost of thinning the allocated area.

Another method of evaluating the additional cost of accessing areas during the planning process would be to perform a cost calculation after each additional node is connected to the existing road/trail network. As a new node is linked the model would calculate the cost of pre-commercial thinning the additional area. This would allow a step-by-step report of the total cost to pre-commercially thin the planning area. An added benefit would be the ability to set a budget. The model would stop allocating area once the user-defined budget is exceeded. A "shadow cost" of connecting an additional node to the network could then be reported.

Also, in terms of planning the access to the allocated areas, using the minimal spanning tree to generate the access trails throughout the planning area can create a problem in that it connects nodes directly without consideration of restrictions or obstacles existing between two nodes. This method could blindly connect two nodes on opposite banks of a river or lake. This is not a practical solution to the network, as the cost of creating access across a river or lake would change the solution. Therefore, better data is needed to describe the impediment required to move along given routes connecting all the nodes to the existing road network.

Another shortcoming of the minimal spanning tree is in the application of the generated network pathways. If the operator is not concerned with having to pass through a given section more than once there is little difficulty with the resulting network. However, if the operator wants to perform only one pass through a section without returning, then another network analysis method is required. The "travelling salesman" network solution (Taha, 1987) would solve this problem, but the time required to solve the network will greatly increase, especially as the number of nodes increases (Sangalli, 1992).

Although the simple minimal spanning tree algorithm does not address obstacles in this version of the planning model, it can still provide estimates of cost savings through better planning than a simple "blanket" treatment of an area. An improvement to the network analysis could be made by determining the impediment of moving from node to node (*eg.* productivity) to apply to the analysis.

5.5 FULFILLING DSS REQUIREMENTS

The methods employed for this model were fairly basic, with only previously tested methodologies incorporated in the planning process. This avoids the "black box" characteristic that can often occur with some models. The decision-maker is more likely to be comfortable with analyses performed using simple algorithms, and is more likely to be aware of the limits and weaknesses that are intrinsic to the method used. Applying a model without understanding its limitations could lead to decisions based on erroneous results.

All density data were derived from field samples, aerial photos, GIS databases. Since the density maps are of the ERDAS© GIS file format, it is possible that remote sensing imagery could be classified and entered directly into the model. Therefore, as quickly as new imagery can be obtained and classified, the data can be updated, and new analyses performed.

6 CONCLUSIONS

The pre-commercial thinning DSS described here is capable of analysing the effects of changes in operational cost, pre-commercial thinning productivity, and selection of areas for different pre-commercial thinning methods. The process involved within the model itself does require some modification and improvement, however, this is to be expected of a prototype model that is still in a research environment and has not been applied to a full operational planning process.

As with any decision-making process, acquisition of valid data is an important and necessary step. The accuracy of the pre-commercial thinning productivity estimates requires some improvement. This could involve the use of additional parameters such as terrain conditions, worker experience, tree species and tree height.

In terms of the modelling process itself, there are some improvements that could be included in later versions. Improvements to the model could include:

1) creating more efficient computer algorithms for the spatial analysis portions of the planning process,

2) applying budgetary constraints during the pre-commercial allocation phases with indicators of the costs and benefits involved for each analysis result, and

3) creating a simplified user interface such as a menu-system for entering planning parameters.

Generally, this model requires more efficient algorithms with the provision of optimization and sensitivity analysis routines. The use of ERDAS© GIS file formats does, however, provide for flexible and easily integrated data from vector-based GIS's, aerial photography, and satellite imagery.

The case studies performed suggest there is the potential for approximately a 12% to 25% savings in total costs by planning the allocation of pre-commercial thinning to specific areas of the stand, as opposed to simply applying a "blanket" treatment across the entire area. The cost savings also greatly exceeded the cost of obtaining the required field data and imagery. After field data collection the savings with the brushsaw pre-commercial thinning were $1,126.42 (18% savings) for the Raith site and $11,251.91 (9% savings) for the Martin site.

Although the costs per hectare were greater for the planned allocations, the thinning effort was focused on a 21% to 28% smaller area. This effort was also in predominantly higher density classes for the planned allocations, which would cause the estimated costs to increase due to lower productivity rates. It was also noted that the model seemed to be most effective in planning pre-commercial thinning in stands containing a lower average density with clumped pockets of higher stem density.

Estimation of pre-commercial thinning productivity definitely needs improvement. The analyses showed that the operational cost estimates were very sensitive to changes in productivity. Improvements might be achieved by including additional parameters such as terrain conditions, worker experience, species composition, season of operation and species height.

There is also the potential for applying this model to planning pre-commercial thinning of other species such as balsam fir and black spruce. However, the sensitivity analysis suggested that better cost savings were achieved when the density occurs in clumped patterns rather than as a continuous density as most often found with balsam fir and black spruce.

Still, applications of this planning model are not restricted to pre-commercial thinning alone. The spatial analysis techniques and network analysis could also be applied to planning of harvest cut blocks within a stand, and the planning of skid trail location to access these blocks. The data in the density images could be altered to represent parameters such as wood volume, ground strength, or terrain conditions. With some modifications to improve flexibility in the input of parameters the model could be used to explore a wide range of problems involving spatial components.

Application of this DSS would be advantageous for investigating the interactions of stand conditions with pre-commercial thinning productivity and operating costs. For example, a contractor could estimate what the operating costs would be for a given site and use these costs to determine how much to bid for a pre-commercial thinning contract. The contractor can determine the best equipment options, the best way to allocate the thinning within the stand, the amount of time required to complete a pre-commercial thinning in a given area and estimate at what point it is no longer profitable to bid on a given contract.

With the results provided by the DSS study, and effort applied to improving the quality of the data and performance of the analysis, it is reasonable to conclude that it is feasible to construct and apply a fully-operational SDSS model to assist planners in pre-commercial thinning decision-making. It is also concluded that it is potentially cheaper and more effective to plan pre-commercial thinning to focus work on areas within stands rather than generally allocating thinning over entire stands.

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APPENDIX I - Pre-commercial thinning production estimates.

Pre-commercial thinning production estimates were obtained from literature sources from Nova Scotia and from Québec. Productivity is expressed in hectares per productive machine hour (ha/PMH). Note that the r^2 values are all less than 0.5, indicating that additional parameters are still needed to describe the variation in productivity.

BRUSHSAW (NSDNR, 1992):

Productivity (ha/PMH) = 32.23 x $SD^{-0.6041}$ (r^2=0.48)

where,

SD = intial stand density (stems/ha) for stands < 6.0 metres tall.

CHAINSAW (NSDNR, 1992):

Productivity (ha/PMH) = 6.148 x $SD^{-0.4925}$ (r^2=0.30)

where,

SD = intial stand density (stems/ha) for stands < 6.0 metres tall.

SILVANA SELECTIVE/FORD VERSATILE (St-Amour and Ryans, 1992):

Productivity (ha/PMH) = 1 / [(7.66E-05 x SD + 3.1296) x 1.053] (r^2=0.41)

where,

SD = intial stand density (stems/ha) for stands < 2.5 metres tall.

OR,

Productivity (ha/PMH) = 1 / [(7.43E-05 x SD + 4.0248) x 1.053] (r^2=0.24)

where,

SD = intial stand density (stems/ha) for "tall" and "short" stands. "Short" stands had an average tree height of 1.8 metres, "tall" stands had an average tree height of 3.0 metres (St-Amour and Ryans, 1992).

APPENDIX II - System costing model.

```
(Source:        Rickards and Savage, 1983.)

GENERAL INFORMATION ABOUT MACHINE:

Machine/system name:                                                 SYSTNAME
No. of working days per year:                                        NDAYS
No. of scheduled hours (SMH) per day:                                NSMH
Machine utilization (%):                                             UTILIZATION
Annual production estimate (m3):                                     ANNPROD
Installed or purchase price ($):                                     PURCHPRICE
Future salvage value ($):                                            SALVAGE
Expected economic life (years):                                      ECONLIFE
Interest rate (%):                                                   IRATE
Fuel consumption (litres/PMH):                                       FUELUSE
Fuel cost ($/litre):                                                 FUELCOST
Engine oil consumption (litres/PMH):                                 OILUSE
Oil cost ($/PMH):                                                    OILCOST
Hydraulic oils and/or lubes (litres/PMH):                            HYDRUSE
Hydraulic oil and/or lube cost ($/litre):                            HYDRCOST
Annual repair and maintenance cost, % of initial purchase price:     REPAIR
Operator wage ($/SMH):                                               WAGE
Fringe benefits cost, % of wage:                                     BENEFITS
Number of operators required per shift:                              NOPERATORS
Insurance/risk cost ($/year):                                        INSURANCE
License cost ($/year):                                               LICENSE

SYSTEM COST SUMMARY:

Interest rate:  RATE = IRATE/100
Present value of salvage value ($):       PVALUE = SALVAGE/(1+RATE)^ECONLIFE
Annual capital cost ($/year):
        ANNCOST = (PURCHPRICE - PVALUE) * ((RATE * ((1 + RATE)^ECONLIFE))/(((1 + RATE)^ECONLIFE) - 1))
                    + (PVALUE * RATE)
Capital cost ($/SMH):    CAPITALCOST = ANNCOST / SMHYEAR
Operator cost ($/SMH):   OPCOST = (WAGE + WAGE * BENEFITS/100) * NOPERATORS
Energy, oil & lube cost ($/PMH): FLUIDSCOST = FUELUSE*FUELCOST + OILUSE*OILCOST + HYDRUSE*HYDRCOST
Repair & maintenance cost ($/year):       MAINTENANCE = PURCHPRICE * REPAIR/100
License & insurance cost ($/year):        COVERAGE = INSURANCE + LICENSE
m3 produced per year:    ANNPROD
Annual operating cost ($/year):
        ANNOPSCOST = ANNCOST + OPCOST*SMHYEAR + FLUIDSCOST*PMHYEAR + MAINTENANCE + COVERAGE
Hourly operating cost ($/SMH):
        HOURLYCOST = CAPITALCOST + OPCOST + (FLUIDSCOST * PMHYEAR / SMHYEAR) + MAINTENANCE / SMHYEAR
                        + COVERAGE / SMHYEAR
Scheduled hours per year (SMH/year):      SMHYEAR = NDAYS * NSMH
Productive hours per year (PMH/year):     PMHYEAR = SMHYEAR * UTILIZATION / 100
m3 produced per SMH:     M3SMH  = ANNPROD   / SMHYEAR
m3 produced per PMH:     M3PMH  = ANNPROD   / PMHYEAR
Cost per m3 ($/m3):      M3COST = ANNOPCOST / ANNPROD
```

APPENDIX III - Sample model output.

```
PRE-COMMERCIAL THINNING PLANNING
1994/ 3/19     18:58:18

CURRENT FILES.

DATA FILES:
 DENSITY GRID MAP .......... d:arpjkrg2.gis
 ROAD ACCESS MAP ........... d:arpjroad.gis
 SYSTEM COSTING MODEL ...... c:\thesis\pctmodel\pctsysts\silvford.cst
 BUFFER DATA FILE .......... c:\thesis\pctmodel\pctdata\roaddata.dat
 PCT PRODUCTION DATA ....... c:\thesis\pctmodel\pctsysts\sf100.pct

OUTPUT FILES:
 PCT INITIAL BUFFER ........ d:buffer01.gis
 PCT NEW BUFFER ............ d:buffer02.gis
 PCT PLANNING REPORT ....... c:\thesis\pctmodel\pctout\arsf100.log
 NEW ROAD ACCESS FILE ...... d:newroad1.gis

MODEL PARAMETERS:
 MINIMUM ELIGIBLE DENSITY .....   3000.00 stems/ha
 MAXIMUM ELIGIBLE DENSITY ..... 999999.00 stems/ha
 DENSITY CONVERSION FACTOR ....    200.00 stems/ha
 MINIMUM NODE AREA ACCESS .....      .2500 ha
 NODE SEARCH INTERVAL .........      .00 m

ROAD CELLS:   578
CREATING BUFFER AROUND INITIAL ROADS.
GENERATING NEW ACCESS NETWORK.
NODE SEARCH HAS DETECTED     18 NODES.
CONNECTING NODES TO INITIAL ACCESS.
INITIALIZED NEW NETWORK.
CREATING BUFFER AROUND NEW ACCESS.

FILE: d:arpjkrg2.gis
   ENTIRE IMAGE:
    # of cells:          22422
    Average density:       773.606
    Std. Deviation:       1277.611
    Minimum:                  .000
    Maximum:              8000.000

   NULLS OMITTED:
    # of cells:           6527
    Average density:      2657.546
    Std. Deviation:        775.356
    Minimum:               400.000
    Maximum:              8000.000


FILE: d:buffer01.gis
   ENTIRE IMAGE:
    # of cells:          22422
    Average density:       399.420
    Std. Deviation:        990.684
```

```
    Minimum:                   .000
    Maximum:               6400.000

   NULLS OMITTED:
    # of cells:            3417
    Average density:       2620.954
    Std. Deviation:         785.337
    Minimum:                400.000
    Maximum:               6400.000


FILE: d:buffer02.gis
   ENTIRE IMAGE:
    # of cells:           22422
    Average density:        584.667
    Std. Deviation:        1196.787
    Minimum:                   .000
    Maximum:               8000.000

   NULLS OMITTED:
    # of cells:            4676
    Average density:       2803.550
    Std. Deviation:         804.155
    Minimum:                400.000
    Maximum:               8000.000
```

IMAGE FREQUENCY DISTRIBUTIONS.

CLASS	INITIAL	ACCESS1	ACCESS2
0	15895	19005	17746
1	0	0	0
2	5	2	2
3	17	9	9
4	35	15	15
5	68	39	39
6	87	48	49
7	154	89	89
8	279	194	200
9	488	313	324
10	429	242	247
11	517	261	273
12	585	255	289
13	711	325	370
14	741	372	500
15	559	271	497
16	685	380	650
17	431	258	409
18	296	145	285
19	177	66	168
20	84	38	82
21	45	24	45
22	32	15	32
23	23	10	23
24	25	13	25
25	11	7	11
26	10	6	10
27	9	8	9
28	5	4	5
29	3	3	3
30	6	4	6
31	0	0	0
32	4	1	4
33	0	0	0
34	1	0	1
35	2	0	2
36	2	0	2
37	0	0	0
38	0	0	0
39	0	0	0
40	1	0	1

PCT PRODUCTION ESTIMATE: TOTAL AREA
SYSTEM: Silvana Selective/Ford Versatile
HOURLY OPERATING COST: $ 67.91/PMH

STEMS/HA	HA/PMH	HA	HOURS	COST
BELOW MINIMUM DENSITY.				
0.	.000	160.19	.00	.00
1000.	.296	14.37	48.55	3297.05
2000.	.289	31.13	107.72	7315.49
SUBTOTAL		205.69	156.27	10612.55
ELIGIBLE DENSITY.				
3000.	.283	16.73	59.12	4014.86
4000.	.276	1.36	4.93	334.64
5000.	.270	.33	1.22	83.00
6000.	.265	.07	.26	17.94
7000.	.259	.03	.12	7.87
SUBTOTAL		18.52	65.65	4458.32
TOTAL		224.21	221.91	15070.86

ROAD COST ESTIMATE

File: d:arpjroad.gis

CODE	CELLS	RATE	COST
CONSTRUCTION			
0	0	.00	.00
1	0	.00	.00
2	0	.00	.00
			$ .00
MAINTENANCE			
0	0	.00	.00
1	100	3.00	300.00
2	478	1.50	717.00
			$ 1017.00

TOTAL ROAD CONSTRUCTION AND MAINTENANCE COST = $ 1017.00

AVERAGE STAND TO ROAD ACCESS DISTANCE
INITIAL ROAD NETWORK
Number of cells: 6527
Average distance: 59.7 m
Maximum distance: 280.0 m

PCT PRODUCTION ESTIMATE: ACCESSED AREA
SYSTEM: Silvana Selective/Ford Versatile
HOURLY OPERATING COST: $ 67.91/PMH

STEMS/HA	HA/PMH	HA	HOURS	COST
BELOW MINIMUM DENSITY.				
0.	.000	190.67	.00	.00
1000.	.296	8.86	29.93	2032.83
2000.	.289	14.84	51.35	3487.36

SUBTOTAL		214.37	81.28	5520.19
ELIGIBLE DENSITY.				
3000.	.283	8.87	31.34	2128.61
4000.	.276	.69	2.50	169.78
5000.	.270	.25	.93	62.88
6000.	.265	.01	.04	2.56
SUBTOTAL		9.82	34.81	2363.84
TOTAL		224.19	116.09	7884.03

ROAD COST ESTIMATE

File: d:arpjroad.gis

CODE	CELLS	RATE	COST
CONSTRUCTION			
0	0	.00	.00
1	0	.00	.00
2	0	.00	.00
			$ .00
MAINTENANCE			
0	0	.00	.00
1	100	3.00	300.00
2	478	1.50	717.00
			$ 1017.00

TOTAL ROAD CONSTRUCTION AND MAINTENANCE COST = $ 1017.00

PCT PRODUCTION ESTIMATE: NEW ROAD ACCESS AREA
SYSTEM: Silvana Selective/Ford Versatile
HOURLY OPERATING COST: $ 67.91/PMH

STEMS/HA	HA/PMH	HA	HOURS	COST
BELOW MINIMUM DENSITY.				
0.	.000	178.09	.00	.00
1000.	.296	9.09	30.71	2085.60
2000.	.289	19.29	66.75	4533.11
SUBTOTAL		206.47	97.46	6618.71
ELIGIBLE DENSITY.				
3000.	.283	15.94	56.33	3825.28
4000.	.276	1.36	4.93	334.64
5000.	.270	.33	1.22	83.00
6000.	.265	.07	.26	17.94
7000.	.259	.03	.12	7.87
SUBTOTAL		17.73	62.86	4268.73
TOTAL		224.20	160.31	10887.44

ROAD COST ESTIMATE

File: d:newroad1.gis

CODE	CELLS	RATE	COST
CONSTRUCTION			
0	0	.00	.00
1	0	.00	.00
2	0	.00	.00
3	150	.00	.00
			$ .00
MAINTENANCE			
0	0	.00	.00
1	100	3.00	300.00
2	478	1.50	717.00
3	0	.00	.00
			$ 1017.00

TOTAL ROAD CONSTRUCTION AND MAINTENANCE COST = $ 1017.00

STARTED : 1994/ 3/19 at 18:58:18.
FINISHED: 1994/ 3/19 at 20:31:10.

APPENDIX IV - Costing models for brushsaws, chainsaws, and Silvana Selective/Ford Versatile.

Machine/system name	Brushsaw	Chainsaw	Silvana/Ford
No. of working days per year	225	225	125
No. of scheduled hours (SMH) per day	8.00	8.00	24.00
Machine utilization (%)	80.00%	80.00%	80.00%
Installed or purchase price:	$850.00	$475.00	$173,000.00
Future salvage value	$0.00	$0.00	$17,300.00
Expected economic life	1.00	1.00	5.00
Interest rate (%)	5.00%	5.00%	5.00%
Fuel consumption per Productive Machine Hour (PMH) ...	1.25	1.25	6.50
Fuel cost per litre	$0.60	$0.60	$0.45
Oil consumption per PMH	0.16	0.16	1.00
Oil cost per litre	$1.35	$1.35	$0.29
Lube consumption per PMH	0.00	0.00	0.00
Lube cost per litre	$0.00	$0.00	$0.00
Annual repair & maintenance cost			
(% of initial purchase price)	200.00%	200.00%	24.00%
Operator wage per SMH	$16.50	$16.50	$18.00
Fringe benefit cost (% of wage)	35.00%	35.00%	0.00%
Number of operators per shift	1	1	1
Insurance cost per year	$50.00	$50.00	$3,300.00
License cost per year	$0.00	$0.00	$50.00

SYSTEMS COST SUMMARY

Interest rate	0.05	0.05	0.05
Present value of salvage value	$0.00	$0.00	$13,555.18
Annual capital cost ($/year)	$892.50	$498.75	$37,505.53
Capital cost ($/SMH)	$0.50	$0.28	$12.50
Operator cost ($/SMH)	$22.27	$22.27	$24.30
Energy, oil & lube cost ($/PMH)	$0.97	$0.97	$3.21
Repair & maintenance cost ($/year)	$1,700.00	$950.00	$41,520.00
License & insurance cost ($/year)	$50.00	$50.00	$3,350.00
Annual operating cost ($/year)	$44,128.54	$42,984.79	$162,991.50
Scheduled machine hours (SMH) per year	1,800.00	1,800.00	3,000.00
Productive machine hours (PMH) per year	1,440.00	1,440.00	2,400.00
Hourly operating cost ($/SMH)	**$24.52**	**$23.88**	**$54.33**
($/PMH)	**$30.64**	**$29.85**	**$67.91**

APPENDIX V - Cell Value Frequency Distributions.

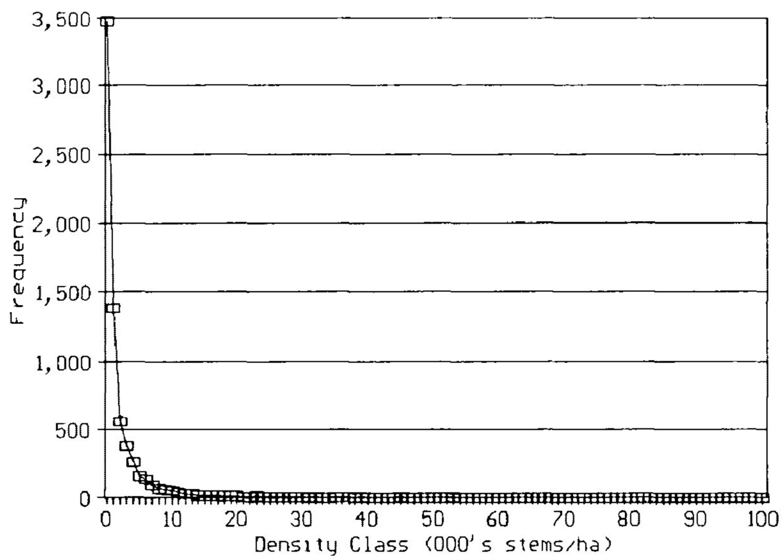

Figure A.1 Density class frequency distribution for the control data Baseline-1 image.

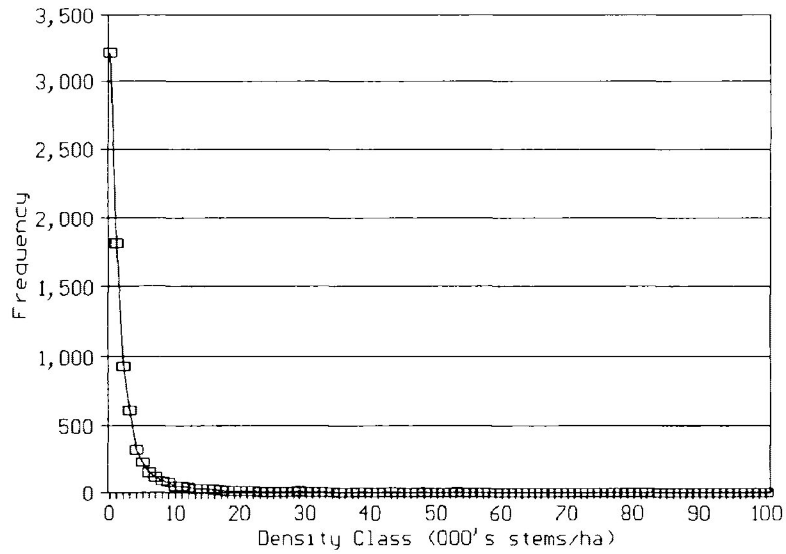

Figure A.2 Density class frequency distribution for the control data Baseline-2 image.

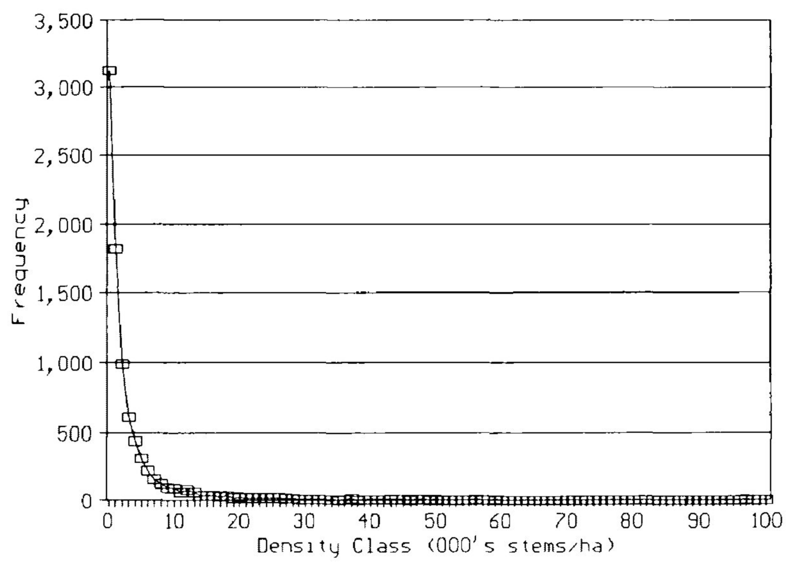

Figure A.3 Density class frequency distribution for the control data Baseline-3 image.

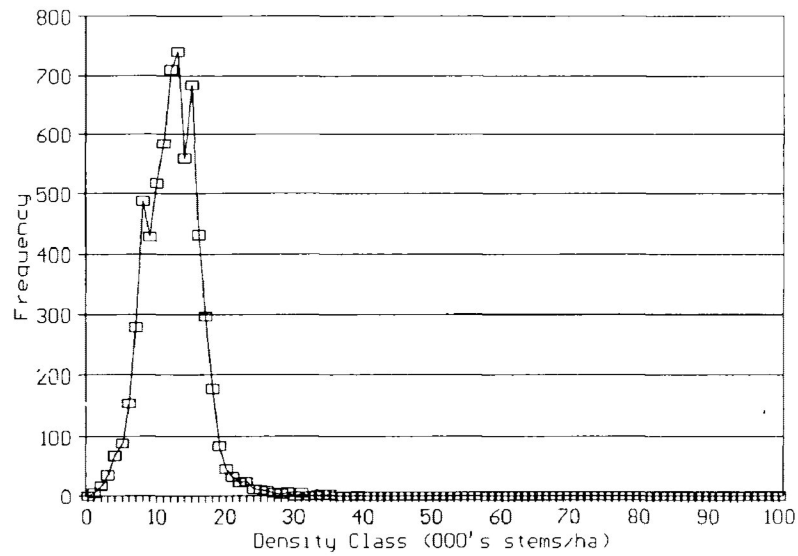

Figure A.4 Density class frequency distribution for the Raith study area image of stands 350, 351, and 376 generated from the field data using the inverse weighted distance method.

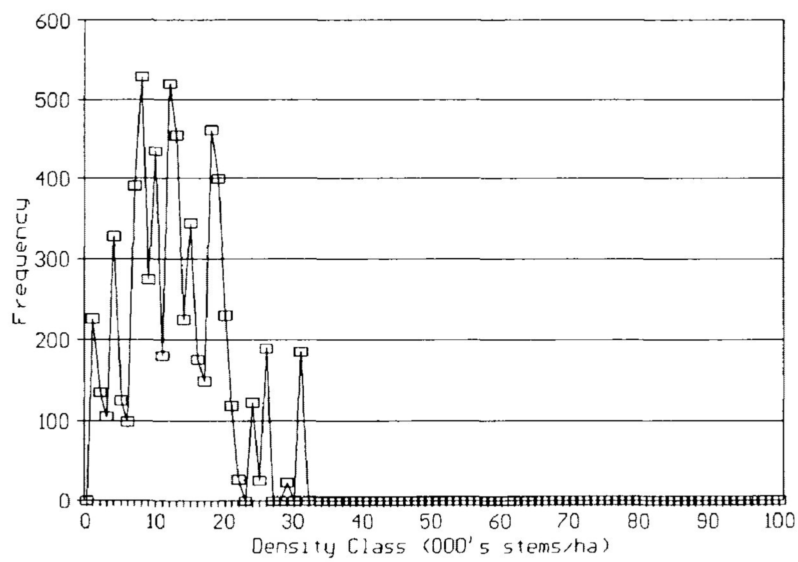

Figure A.5 Density class frequency distribution for the Raith study area image of stands 350, 351, and 376 generated from the field data using the nearest point method.

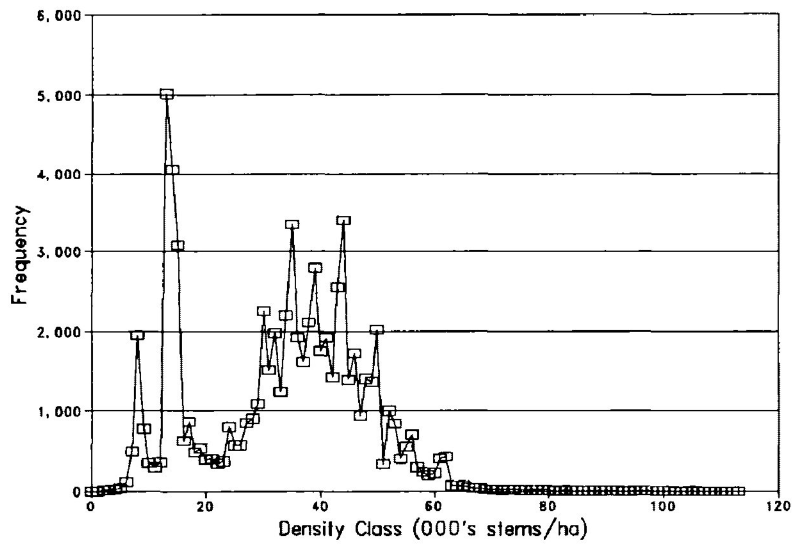

Figure A.6 Density class frequency distribution for the Martin study area image generated from the field data using the inverse weighted distance method.

APPENDIX VI - Pre-commercial thinning cost estimates.

Table A.1 Pre-commercial thinning cost estimates for "blanket" thinning of the chainsaw, brushsaw, and Silvana/Ford systems for the Raith interpolated field data image.

DENSITY	AREA	PRE-COMMERCIAL THINNING COST ESTIMATES		
		Chainsaw	Brushsaw	Silvana/Ford
(stems/ha)	(ha)	($)	($)	($)
1 000	14.37	2,092.48	886.06	3,297.05
2 000	31.13	6,364.84	2,917.41	7,315.49
3 000	16.73	4,196.71	2,002.72	4,014.86
4 000	1.36	394.14	193.85	334.64
5 000	0.33	105.92	53.79	83.00
6 000	0.07	24.58	12.77	17.94
7 000	0.03	11.34	6.01	7.87
TOTAL	64.02	13,190.01	6,072.61	15,070.86

Table A.2 Pre-commercial thinning cost estimates for "blanket" thinning of the chainsaw, brushsaw, and Silvana/Ford systems for the Martin interpolated field data image.

DENSITY	AREA	PRE-COMMERCIAL THINNING COST ESTIMATES		
		Chainsaw	Brushsaw	Silvana/Ford
(stems/ha)	(ha)	($)	($)	($)
1 000	36.76	5,352.69	2,266.60	8,434.04
2 000	128.14	26,198.73	12,008.54	30,111.80
3 000	28.93	7,257.09	3,463.17	6,942.63
4 000	24.93	7,225.13	3,553.44	6,134.44
5 000	56.70	18,198.08	9,241.78	14,260.88
6 000	102.54	36,011.52	18,704.92	26,279.44
7 000	101.64	38,406.43	20,358.44	26,652.18
8 000	106.70	43,043.03	23,191.04	28,530.03
9 000	74.35	32,163.96	17,260.34	20,277.79
10 000	31.33	14,170.25	7,742.91	8,720.33
11 000	16.53	7,832.35	4,329.64	4,697.17
12 000	10.12	5,034.86	2,793.96	2,924.64
13 000	1.59	818.32	464.05	469.49
14 000	0.97	517.05	294.31	291.49
15 000	0.65	359.31	205.35	198.84
16 000	0.27	154.99	88.97	84.11
17 000	0.23	134.62	78.31	72.99
18 000	0.07	42.64	24.66	22.53
19 000	0.10	62.19	36.48	32.81
20 000	0.02	12.70	7.57	6.66
22 000	0.01	6.63	3.98	3.45
TOTAL	722.58	243,002.57	126,118.46	185,147.70

Table A.3 Pre-commercial thinning cost estimates for the chainsaw, brushsaw, and Silvana/Ford systems for the planned access trails.

DENSITY (stems/ha)	AREA (ha)	PRE-COMMERCIAL THINNING COST ESTIMATES Chainsaw ($)	Brushsaw ($)	Silvana/Ford ($)
Untreated	17.91	0.00	0.00	0.00
1000	9.09	1,323.63	560.49	2,085.60
2000	19.29	3,944.02	1,807.80	4,533.11
3000	15.94	3,998.54	1,908.15	3,825.28
4000	1.36	394.14	193.85	334.64
5000	0.33	105.92	53.79	83.00
6000	0.07	24.58	12.77	17.94
7000	0.03	11.34	6.01	7.87
TOTAL	64.02	9,802.17	4,542.86	10,887.44

Table A.4 Pre-commercial thinning cost estimates for the chainsaw, brushsaw, and Silvana/Ford systems for the planned access trails.

DENSITY (stems/ha)	AREA (ha)	PRE-COMMERCIAL THINNING COST ESTIMATES Chainsaw ($)	Brushsaw ($)	Silvana/Ford ($)
Untreated	4504.56	0.00	0.00	0.00
1 000	18.24	2,656.02	1,124.69	4,184.99
2 000	30.68	6,272.83	2,875.23	7,209.74
3 000	12.50	3,135.61	1,496.35	2,999.74
4 000	18.53	5,370.30	2,641.20	4,559.61
5 000	54.43	17,469.59	8,871.82	13,690.00
6 000	99.93	35,094.74	18,228.73	25,610.41
7 000	98.22	37,113.89	19,673.29	25,755.22
8 000	104.00	41,953.66	22,604.10	27,807.97
9 000	73.26	31,692.30	17,007.23	19,980.44
10 000	30.83	13,944.10	7,619.34	8,581.16
11 000	16.23	7,690.20	4,251.06	4,611.92
12 000	10.00	4,975.16	2,760.83	2,889.96
13 000	1.52	782.29	443.62	448.82
14 000	0.97	517.05	294.31	291.49
15 000	0.62	342.73	195.87	189.67
16 000	0.24	137.77	79.08	74.77
17 000	0.23	134.62	78.31	72.99
18 000	0.06	36.55	21.13	19.31
19 000	0.10	62.19	36.48	32.81
20 000	0.02	12.70	7.57	6.66
22 000	0.01	6.63	3.98	3.45
TOTAL	5,075.19	209,400.90	110,314.30	149,021.10