Forest Planning with Consideration to Spatial Relationships

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Abstract

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This thesis deals with approaches that can be used to consider spatial relationships in long term forest planning. In the thesis the optimization approach is used, *i.e.* variables in some way describing the spatial relationships are processed by the solution algorithm, and the spatial layout of harvest activities or habitats is generated by the optimization. In the first part of the thesis, the core area was tested as a criterion for forming contiguous areas of old forest while maximizing the net present value of future forest management. The core area concept was applied in different case studies both to a simulated forest landscape and an actual one in northern Sweden. Because of the non-linear characteristics in the model formulations the problems were solved with a heuristic method, in this case simulated annealing. To increase the scope of the models to include the forest-wide constraints normally encountered in forest planning, a new approach that integrates linear programming with simulated annealing was also tested.

The second part of the thesis deals with the aggregation of the harvests in time and space. A new criterion, based on the clustered volume of timber to be harvested, was developed to obtain aggregation of harvested areas. The criterion was in a case study applied to a landscape where high levels of consideration are also paid to biodiversity and recreation. Finally, a new model was developed that could be solved with exact solution techniques for clustering the harvest and the areas set aside as reserves. In contrast to the other models this was applied to a landscape where the decision units were pixels (20*20meters) instead of stands.

The results show that it is possible to include considerations of spatial relationships in long-term forest planning, also when the problems are of a size found in real-world situations. For problems where the forest-wide constraints are few and only relate to the spatial aspects it seems that heuristics alone is adequate. When more forest-wide constraints are added to the problem, a suitable approach could be to combine two solution techniques into one integrated solution procedure. The experiments with exact solution techniques suggest that, at least when pixels are used as the primary decision unit, also relatively large problems can be solved exactly if proper formulations can be found. Finally, the results indicate that using effective methods for solving spatial problems will reduce the cost connected to taking spatial considerations.

Keywords: connectivity problems, fragmentation, harvest scheduling, mathematical programming, spatial structure, strategic planning.

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"Whether you think you can
or can't, you're right."
- Unknown

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Appendix

Papers I-V

This thesis is based on the following papers, which will be referred to by the corresponding Roman numerals in the text:

I. Öhman, K. and Eriksson, L.O. 1998[1]. The core area concept in forming contiguous areas for long term forest planning. *Canadian Journal of Forest Research* 28:1032-1039.

II. Öhman, K. 2000[1]. Creating continuous areas of old forest in long term forest planning. *Canadian Journal of Forest Research* 30:1817-1823.

III. Öhman, K. and Eriksson, L.O. 2001[2]. Allowing for spatial consideration in long term forest planning by linking linear programming with simulated annealing, *Forest Ecology and Management* .In Press.

IV. Öhman, K. and Lämås, T. 2001. Clustering of harvest activities in multi-objective long-term forest planning, submitted manuscript.

V. Öhman, K. 2001. Clustering of harvest activities and nature reserves with mixed integer programming, submitted manuscript.

Introduction

Background

There is an increasing interest in considering goals other than timber production in forest planning, *i.e.* the process of deciding what activities to perform when and where. These new goals require attention to be paid to spatial relationships. For example, to maintain biodiversity, key questions that must be addressed include how the size, shape and distribution of harvest areas compare with the spatial characteristics of natural disturbances. These issues are important since both the spatial structure, and non-spatial characteristics of stands affect ecological processes and organisms (Forman 1995; Collinge 1998; Hunter 1999). Increasing pressure to meet various ecological goals, such as reducing the fragmentation of old forest, maintaining uncut borders around key habitats and creating corridors between valuable habitats, have stimulated interest in spatially evaluating different harvest strategies. Therefore in some cases, it is even more important to know how a clearcut is spatially laid out than to know how many hectares it covers (Harris 1984; Franklin and Forman 1987). Spatial evaluation of different management options is also necessary for financial goals. For example, it is generally recognized that it is more expensive to harvest widely dispersed areas than areas that are clustered in space (Baskent and Jordan 1991; Gustafsson 2000). Further, the spatial structure of the forest affects not only its ecological and economic value, but also its value for recreational purposes since the recreational value of a stand is a function of both its non-spatial characteristics, and features of the surrounding stands (Brown *et al*. 1990; Pukkala *et al*. 1995)

Obviously, there are many reasons to why forest planning should include consideration of spatial relationships and subsequently forest planning must be built on spatial models. A spatial model differs from a non-spatial model in at least two ways. First, in a spatial model each stand or unit has to be treated as an individual unit, whereas in a non-spatial model the stands often are aggregated into strata. Second, in a spatial model the relative locations of stands or habitats are documented and recognized, *e.g.* stand number 1 may be adjacent to stands number 2, 3, and 7 (Baskent and Jordan 1991). However, the existing approaches to forest planning to a large extent lack the means to include spatial considerations. Therefore, this thesis deals with ideas and approaches for including consideration of spatial relationships in long term forest planning. The following sections will focus on the key concepts in the title of the thesis: forest planning and spatial relationships. Different ways of including spatial relationships in the planning process will be discussed. Key characteristics of spatial problems and different techniques for solving spatial problems will also be discussed. Further, examples will be given of various problems that include spatial relationships.

Forest planning versus spatial considerations

Essentially, there is no fundamental difference between forest management planning and planning for other purposes. Like planning in other businesses, it consists of providing the decision maker with information so he or she can identify the best of all possible courses of action. Forest planning has several distinctive features. First, in forest planning there are diverse, and sometimes conflicting, goals. The goals for a single estate owner could include: maximizing the net present value (NPV) of future forest management, maximizing the future harvest volume, maintaining biodiversity, creating recreation areas *etc*. Second, forest planning is complicated by the complexity of forest systems, because of many different interacting processes, large areas, incomplete data *etc*. Therefore, there is typically a high degree of uncertainty when predicting the outcome of different economic and ecological variables. Finally, forest planning characteristically requires very long time frames, for reflecting the nature of forestry problems. This further complicates the planning and makes it likely that unpredictable events will occur, see *e.g*. Hunter 1990; Hytönen 1995, Pukkala 1998; and Davis *et al*. 2000.

Due to this complexity, forest planning is usually divided into a hierarchical structure with strategic, tactical, and operational planning levels (Weintraub and Cholaky 1991; Davis and Martell 1993; Lämås 1996; Davis *et al*. 2000). The aim of the strategic planning is to decide which general strategies can be applied and which outputs should be produced over a long planning horizon, *e.g.* 50-100 years. One important aim of strategic planning is to define the allowable cut, *i.e.* the total harvesting volume under sustainable management. In the strategic plan general targets for nature conservation are also set, in some cases with the help of ecological landscape planning (ELP). ELP is a recently developed tool for balancing timber production with the maintenance of biodiversity at the landscape level (Törnquist 1996). Tactical planning typically looks five to ten years into the future and the aim here is to translate the goals from the strategic plan to smaller units of land. The main output from the tactical plan is a register of well-inventoried units that should be harvested in the medium term, *e.g.* within five years. Finally, operational planning is short term and looks from a month to seldom more than a year in the future. In the operational planning phases the forest operations are scheduled, and objectives set in higher levels are implemented.

Traditionally, considerations of spatial relationships are not included in the planning at the strategic level. Instead, harvest and silvicultural activities are scheduled in the tactical planning stage to meet defined spatial constraints. One reason for this is that in strategic planning the forest is often represented by strata and, thus, spatial relationships between individual units cannot be realistically modelled (Daust and Nelson 1993; Church *et al*. 1998). This is the case in, e.g. The Forest Management Planning Package (FMPP), which is among other systems, used in Swedish forestry (Jonsson *et al*. 1993). However, not including the spatial constraints and objectives at the strategic level could lead to misleading results, or plans that are impossible to implement. For example both, Daust and Nelson (1993) and Clements *et al*. (1990) found that the sustained yields developed by strata based models were higher than the estimated yield when spatial constraints were included in the models.

Instead of including spatial considerations at the strategic level it is often assumed to be sufficient to require merely that a certain amount of old forest (for instance) be retained. But using aggregate amounts of habitats at the strategic level when patch shape, size and distance between habitats are all important, can result in overestimates of the amount of suitable habitat present (Davis *et al*. 2000).

Spatial considerations in the optimization process

Exogenous and endogenous approaches

There are two main approaches, the exogenous and the endogenous approach, for incorporating consideration of spatial objectives into the planning process (Kurttila 2001a). In the exogenous approach, the optimization does not include any spatial information but it takes into account predetermined spatial constraints. This can be done by manipulating the simulation of permitted treatment schedules in such a way that only schedules that generate a certain spatial structure are allowed (*e.g.* Nalli *et al*. 1996; Naesset 1997; Fries and Lämås 2000; Kangas *et al*. 2000). One example of a case where the exogenous approach could be useful is when set aside areas are decided in advance, *e.g.* key habitats. In the endogenous approach, variables that in some way describe the spatial relationships are processed by the solution algorithm, and the spatial layout is generated by the optimization (Kurttila 2001a). Therefore, the endogenous or optimization approach can evaluate a huge number of alternatives and allow trade-off analysis between different objectives, which might be impossible with the exogenous approach (Hof and Bevers 1998). The endogenous approach should be used when spatial habitats are not decided in advance and could be changed over time *e.g.* corridor connections between valuable habitats (Kurtilla 2001b).

Characteristics of spatial problems

Including spatial objectives and considerations into the optimization will, of course, increase the complexity of the task (Hof and Bevers 1998; Krcmar-Nozic *et al*. 1998; Martell *et al*. 1998). One reason for this is that to represent spatial relationships integer variables must be used (Daust and Nelson 1993; Murray and Snyder 2000). Another problem is connected with accounting for the response of the output of interest to the different spatial configurations of management actions. Typically, in non-spatial forest planning the response of the output of interest, *e.g.* the volume harvested in a certain period, is expressed as a sum over a number of treatment schedules[3] for a number of management units. However, problems that involve spatial consideration are often affected by interdependencies between individual management units, *i.e.* the output response is dependent on actions taken in neighbouring units (Hof and Bevers 1998; Hoganson *et al*. 1998). Or, more precisely, the production functions for the units are no longer homogeneous of degree one with respect to area. Thus, the outputs can no longer be expressed in terms of a linear combination of treatment schedules (Eriksson 1983). This causes difficulties, since combinations of non-linear functions and integer variables are difficult to solve and many of the planning systems available today are designed to handle linear functions and continuous variables, *e.g.* FOLPI (Manley *et al*. 1991), FORPLAN (Johnson *et al*. 1986), GAYA-LP (Hoen 1996), MELA (Siitonen and Nuutinen 1996), and SPECTRUM (Camenson *et al*. 1996).

Mathematical programming

The above mentioned problems in connection with the choice of the endogenous approach limit the techniques that could be used for solving the basic management problem, *i.e.* finding the set of treatment schedules that maximizes the objective(s). Mathematical programming is a collective name for a group of techniques that efficiently search through problems described by an objective function and a set of constraints (Dykstra 1984; Williams 1985; Davis *et al*. 2000).

Depending on the model structures, various solution techniques could be used to solve the stated management problem. Linear programming (LP) is one of the most widely used methods for solving long-term management problems (Johnson and Scheurman 1977; Lappi 1992). A major advantage of LP is its computational efficiency. Another is that the constraint matrix can be easily formed from treatment schedules generated by practically any stand projection model. However, a basic assumption of LP is linearity, *i.e.* the objective function and the constraints must be strictly linear over the domain (Dykstra 1984; Nash and Sofer 1996). For forest planning problems this implies that (a) the output must be constant per hectare for a given treatment schedule and unit and (b) different treatment schedules can be assigned to different parts of a unit. Hence, the scope for using LP is limited with the endogenous approach. In such cases other techniques have been used, such as integer programming (IP) and mixed integer programming (MIP) (Williams 1985). IP and MIP differ from LP since they require all or some variables to be integers. One disadvantage with IP and MIP is that no method is available that solves all problems involving integer variables as efficiently as the simplex method for LP (ReVelle 1993). The size of the problems that can be solved is generally much smaller with IP and MIP compared to LP. It is therefore advantageous to formulate models that favour integer or near integer

[3] A treatment schedule is a set of treatments applied from period 1 onwards for a given management unit.

solutions in the relaxed LP solutions, or models that can be solved with as few branches and bounds as possible (Snyder and Revelle 1996a; ReVelle 1993). For large-scale problems or problems involving non-linear relationships, which are often encountered when there are spatial constraints, many researchers have instead used heuristic methods (*e.g.* Lockwood and Moore 1993; Yoshimoto *et al.* 1994; Bettinger *et al.* 1997; Richards and Gunn 2000). A heuristic method is a technique that seeks good solutions to a stated problem at a reasonable computational cost without guaranteeing optimality, or even feasibility (Reeves 1993).

Examples of problems including spatial relationships

In general, there are two main categories of problems dealing with spatial relationships between management units in forest planning. I will here call them dispersing and connectivity problems. Between these two main categories of problems (dispersing and connectivity) a third type of problem can be distinguished, in which the focus is to adjust the spatial structure of the forest to meet the requirements of a certain species. Development of species-specific approaches can be found in various studies such as Bettinger *et al.* (1997); Hof *et al.* (1997); Bevers and Hof (1999) and Hof *et al.* (1999).

Dispersing problems focus on keeping spatial elements with certain conditions *e.g.* clear-cuts and different habitat types apart from each other in the landscape. One example of a dispersing problem is to maximize the edge effect between adjacent stands (Bertomeu and Tomero 2001). Another, similar kind of dispersing problem aims to avoid large open clear cuts in the landscape. This problem has been the most intensively studied types of problem with spatial components in forestry literature. Two different approaches have been used to control the size of clear-cuts, the unit restriction model and the area restriction model (Murray 1999).

In the unit restriction model, the sizes of the individual management units are assumed to be near the maximum opening size. If one unit is scheduled for harvest all adjacent units are restricted from harvest until the regeneration in the cut unit has progressed for a defined minimum time. The unit restriction model can be formulated as either an IP or a MIP problem and exact techniques can be used to solve the stated problem (Snyder and ReVelle 1997). The traditional approach is to generate one constraint for each pair of neighbouring management units (*e.g.* Nelson and Brodie 1990; Murray and Church 1995; Snyder and ReVelle 1996b). The general form of the pairwise constraint for a one period problem is:

$$X_i + X_j \leq 1 \qquad \forall i \in I, \forall j \in N^i \qquad (1)$$

where i is the index, I is the set of planning units, and N^i is the set of units adjacent to i. If unit i is to be harvested then X_i=1 and if unit i is not to be harvested then X_i=0. Since the pairwise approach generates a large number of constraints many studies have aimed to decrease the number of necessary constraints (Jones *et al*. 1991; Murray and Church 1995; McDill and Braze 2000). An example of an approach that reduces the number of constraints is the compartmental approach where one constraint is generated for each management unit and all of the units adjacent to it (Torres-Rojo and Brodie 1990; Murray and Church 1995). The general form of the compartmental constraint for one period problem is:

$$n_i X_i + \sum_{j=1}^{N^i} X_j \leq n_i \qquad \forall i \in I \tag{2}$$

where n_i is the number of units that are adjacent to unit i. However, the number of constraints is today of less concern as many solvers are available which accept formulations with almost unlimited numbers of constraints. Much of the work being done today instead concentrates on improving the efficiency of obtaining solutions (especially in terms of reducing the solution time) and on reducing the difficulties involved in generating the constraints (McDill and Braze 2000; Weintraub *et al*. 2000).

In the area restriction model the size of the individual treatment units are well within the maximum opening size. Harvesting adjacent units is therefore allowed as long as the total contiguous harvested area is less than the maximum opening size. Area restriction models are much more difficult to solve since it is not possible to decide in advance all the possible combinations of harvested units (Murray 1999; Richards and Gunn 2000). These problems have been solved with heuristic methods because of the non-linear characteristics of the area constraint (Lockwood and Moore 1993; Clark *et al*. 2000; Richards and Gunn 2000).

Connectivity problems focus on aggregating stands with certain conditions. These problems often have a different nature from dispersing problems depending on the criteria and constraints used for ensuring that stands or units with certain conditions are brought together. While dispersing problems can usually be formulated with constraints on the management actions, connectivity problems often use an additional criteria for forcing the stands or habitats together *e.g.*, core area (Papers I-III), effective volume (Paper IV) or interior conditions (Paper V). Consequently, the approaches used for solving these types of problem differ too, and in many cases it is not possible to formulate models that could be solved with exact solution techniques.

A typical example of a connectivity problem is to create contiguous areas of old forest in order to minimize the fragmentation (Papers I-III and V). Unfortunately, in the forestry literature there have been very few studies that aimed to aggregate old forest in the optimization in long term forest planning. A few examples of problems that result in aggregated areas of old forest can be found in Hof and Joyce (1993); Clements *et al*. (1999); and in Papers I-III. Another connectivity problem is clustering the harvest in space and time (Papers IV and V). Examples of studies that used a heuristic technique for solving this problem can be found in Holmgren and Thuresson (1997); Lu and Eriksson (2000) and Lind (2000). A third example of a problem that could be described as a connectivity problem, since the goal is to connect different areas in a landscape, is deciding when and where to build roads. The road building issue was one of the first spatial aspects to be included in forest management models. This problem could be formulated as an MIP problem and solved with exact solution techniques (Kirby *et al*. 1986; Church *et al*. 1998; Weintraub *et al.* 2000). For solving larger road building problems heuristic techniques have also been used (Nelson and Finn 1990; Richards and Gunn 2000). A similar type of connectivity problem is the delineation of wildlife corridors. Also this type of problem can be formulated such that exact solution methods can be used (Sessions 1992; Williams 1998).

Objectives

The objective of the work described in this thesis was to develop approaches for including consideration of spatial relationships in long term forest planning. The motives for including such considerations could be economic, ecological or recreational. The spatial relationships between units should be taken into account simultaneously with other goals of forest planning such as maximizing the NPV of the future forest management. The shared feature of the spatial problems in the thesis is that they all aimed to create connectivity. A schematic view showing the domain spanned by the work in the thesis is available in Fig 1. Since many spatial studies must cover a large area for reflecting the nature of the problems they address, the landscape perspective is emphasized in the thesis. Further, the presented approaches are adapted to situations with a single decision maker.

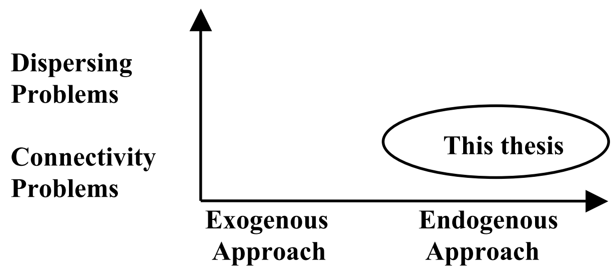

Figure 1: A schematic view of approaches and problems in planning with spatial relationships, showing the domain spanned by the work described in this thesis.

The specific objectives of the papers were:

Papers I and II: To investigate the usefulness of the core area concept in long term forest planning for forming contiguous areas of old forest. The concept was evaluated by solving the long term planning problem of maximizing economic efficiency while creating contiguous areas of old forest. While Paper I was done on a simulated forest landscape, Paper II was done on a real landscape.

Paper III: To test a method that integrates LP with a heuristic method for including spatial objectives into long term forest planning. The problem was here extended to include other forest-wide constraints that are normally found in long-term forest planning as well as maximizing the economic efficiency and creating contiguous areas of old forest.

Paper IV: To present an approach for clustering harvest activities in time and space in long-term forest planning when also paying attention to aspects related to recreation and biodiversity.

Paper V: To present a model for clustering harvest activities and areas to be set aside as nature reserves that could be solved by MIP. The two clustering requirements were incorporated into an NPV-maximizing model with restrictions on the volume harvested in the first period. The problem was solved with pixels smaller than ordinary stands, (20*20meters), as the primary decision units.

Summary of Papers I-V

Papers I-II

These papers investigate the possibilities of using the core area concept in long term forest planning. The core area for a stand is the area consisting of old forest that is free of edge effects from the surrounding forest, *i.e.* core area is a function of patch size, shape and the nature of the adjacent habitats, Fig. 2 (Baskent and Jordan 1995). In both papers the management goals were to maximize the NPV and decrease the fragmentation of old forest, *i.e.* to create contiguous areas of old forest over time in a landscape.

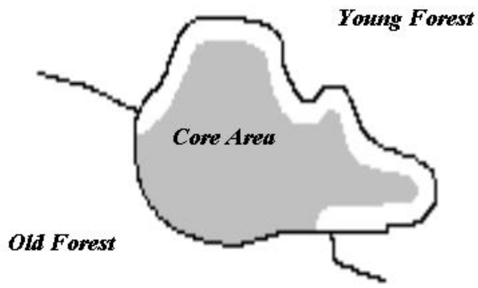

Figure 2. The core area is the area of a stand or unit that is not affected by edge effects from surrounding areas. It is a function of stand size and shape, and the nature of surrounding habitats. The stand in the figure is surrounded partly by forest that causes edge effects and partly by forest that does not cause edge effects. Therefore, only the shaded part consists of core area.

In Paper I the stated model consisted of maximizing the NPV over an infinite time horizon subject to different demands of core area. In a case study the suggested model was applied to a simulated landscape consisting of 200 stands. The planning horizon was divided into 10-year periods, where the core area demand extended over the first 100 years. The only silvicultural measure allowed was clear cutting, with appropriate regeneration measures following the harvest. The definition of old forest was based on an age criterion in which two different ages, 80 and 120 years, were tested. Furthermore, only stands with an age less than 50 years were considered to cause edge effects on surrounding old forest habitats. Finally, two different edge widths for calculating the core area, 32 and 64 meters, were tested.

In Paper II the model was supplemented to include a criterion concerning the amount of edge habitats, *i.e.* the difference between the total amount of old forest and the amount of core area. The purpose of this criterion was to allow additional weight to be placed on aggregation. In a case study the approach was applied to an authentic landscape consisting of 755 stands in northern Sweden. The planning horizon was divided into 5-year periods, where the spatial demands extended over the first 100 years. The case study was extended to include thinning as an allowed silvicultural measure. Unlike the definition of old forest in Paper I the definition used in this paper was linked both to an age criterion and to previous thinnings. To simplify calculations all stands that were not composed of old forest, wetlands, impediments, or lakes were assumed to cause edge effects on surrounding habitats. As in Paper I, two different edge widths were tested: 30 and 60 m.

Because of the non-linear characteristics in the model formulation, the problems in Papers I and II were solved with a heuristic method called simulated annealing (SA) (Laarhoven and Aarts 1987). As a result, the core area demands are accounted for by penalty functions in the objective functions in both Papers I and II. In Paper II, the second requirement regarding the edge habitats, *i.e.* the difference between the total amount of old forest and the amount of core area, was weighted against the NPV. In both Papers I and II reference problems were solved, for estimating the cost of allowing for spatial considerations. In these problems there was only a requirement for a certain amount of old forest, *i.e.* no spatial consideration was taken into account.

In Paper I distinct aggregations of old forest were created irrespectively of the edge width. Further, an increase in edge effect substantially increased the aggregation of old forests. The spatial layout of old forests can be compared with the reference case where the remaining old forest was dispersed over the landscape, Fig 3.

a) b)

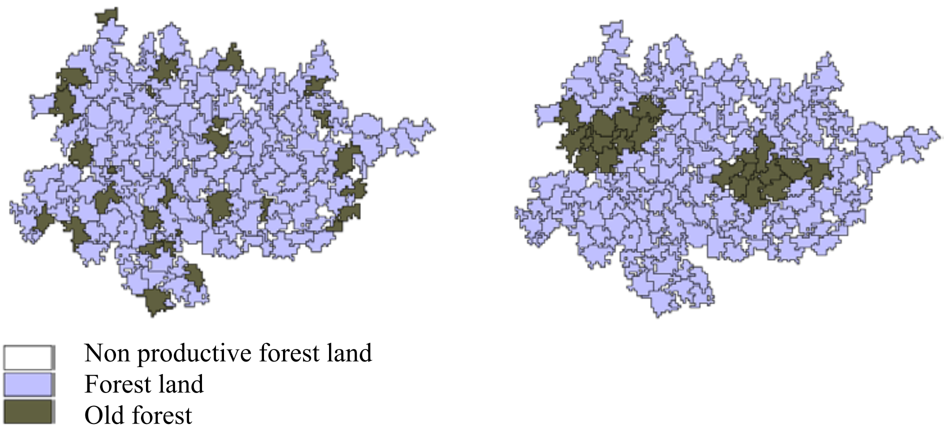

Figure 3.a) The formation of old forest in period 10 a) without spatial consideration b) with spatial consideration. (Paper I)

The results from Paper I are to some extent in contrast to the results in Paper II, where a requirement for a certain amount of core area alone did not create aggregations of old forest, Fig 4a. In Paper II an increase in edge effect caused only a marginal increase in the aggregation of old forest. Here distinct aggregations of old forest were created only when both a core area requirement and consideration of the amount of edge habitats were included in the problem formulation, Fig. 4b. The cost of taking spatial considerations into account was modest in Paper I. However, in Paper II the decrease in NPV was significant when consideration of both the core area requirement and the amount of edge habitats was included in the model formulation *i.e.* if distinct areas of aggregated old forest were created. One reason for the difference in the results is that it was more difficult to create old forest in Paper II. In Paper I stands forming a continuous area of old forest harvested at the same time became old forest in the same time frame in the future. This is different to the case in Paper II, where two stands that were harvested at the same time did not necessarily become old forest in the same period. Further, in Paper II there was an extra cost associated with creating old forest since profitable thinnings may have to be omitted. The solution time was substantial for both studies. In Paper I the solution time was one hour for solving one version of the management problem and in Paper II the solution time was almost 4 hours. However, it should be noted that the solutions were obtained on different computers with different programs.

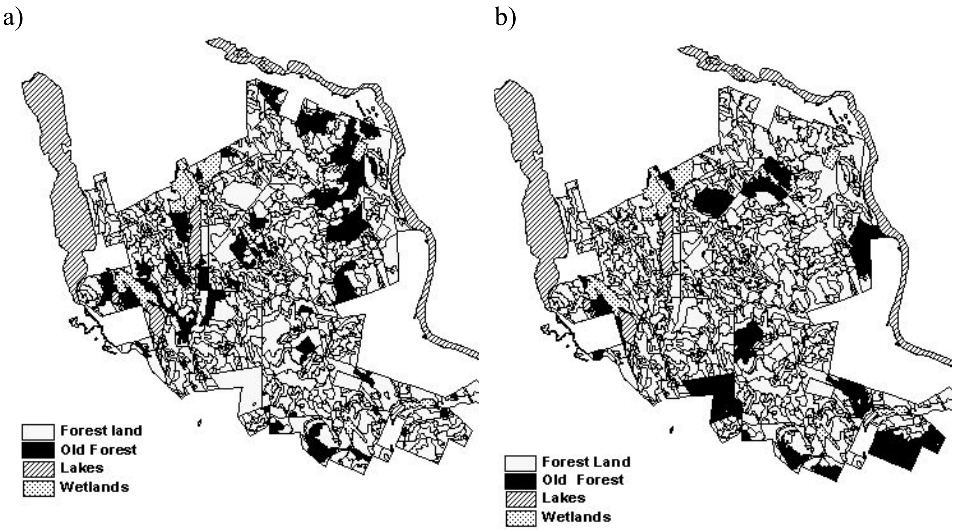

Figure 4.The formation of old forest in the 20th period a) without consideration of the amount of edge habitats b) with consideration of the amount of edge habitats (Paper II)

Paper III

In Paper III the forest management scenarios handled in Paper II were extended to include non-spatial, forest-wide constraints such as harvest flow and inventory requirements as well as the requirements to maximize NPV and create contiguous areas of old forest. The demand for contiguous areas of old forest was expressed in this model formulation in a similar way to that in Paper II. The purpose of this was to allow additional weight to be placed on aggregation. Since the non-spatial part of the problem can be solved with an exact solution technique and the spatial part needs to be solved with a heuristic method such techniques were combined. Two different approaches that combine LP with SA into one integrated solution procedure were tested. For comparison a third approach that used only SA for solving the complete problem was also tested, Fig 5.

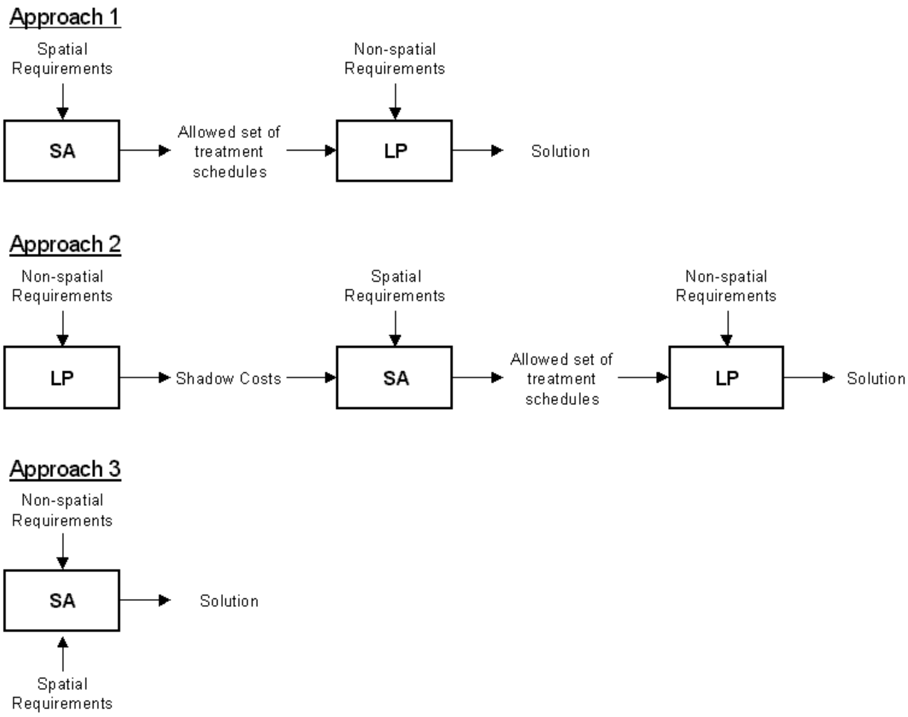

Figure 5.The solution processes for the three approaches explored in Paper III.

In the first approach, the solution algorithm started by solving the spatial part of the problem with SA, without considering the non-spatial forest-wide constraints. The remaining part of the planning problem was then solved with LP. The information that passed from the SA algorithm to the LP part was the set of treatment schedules that gave rise to the same spatial layout of old forest in all periods as given by the solution to the SA algorithm. The rationale of the second approach was that the SA algorithm would produce better solutions if it was fed with information about constraint costs derived using LP. Therefore, the second approach began by solving the problem with LP, including consideration of the forest-wide constraints but without consideration of the spatial constraints. This was then followed by SA and LP, as in the first approach. The information transferred from the LP to the SA algorithm was the shadow costs, or dual solution, of the LP problem. It was brought to the SA analysis via the reduced costs of the treatment schedules. In the third approach the entire problem was solved by SA.

In a case study all three approaches were applied to the landscape addressed in Paper II. In the case study, sensitivity analysis was used to investigate whether more demanding forest-wide restrictions affect the efficiency of the approaches. In this Paper a reference problem was also solved for estimating the cost of including spatial considerations. This was formulated as an LP problem with restrictions on the volume harvested, the ending inventory and the amount of old forest, *i.e.* no spatial consideration was taken into account.

All three approaches formed contiguous areas of old forest even if, for approach 3, the old forest was less aggregated when the harvest flow requirements were more demanding. The aggregation achieved could be compared to the solution of the reference problem, in which the old forests were dispersed over the landscape. Also, with respect to the NPV, approach 3 was less effective than approaches 1 and 2. The difference in the NPV between approaches 1 and 2 was very small. However, compared to the reference problem the cost of taking spatial considerations into account was significant for all three approaches.

Paper IV

In Paper IV a new model for maximizing the NPV and clustering harvest activities was presented. Clustering harvest operations could be desirable to reduce the costs associated with building roads and moving harvest equipment from one area to another. The approach for clustering the harvest in time and space in this study was based on the effective volume for stand, *i,* in period, *p*, EV_{ip} ,Fig 6. The effective volume for stand *i* in period *p* (if the stand is harvested) is equal to the sum of the harvested volumes from stand *i* and neighbouring stands in period *p* and adjacent periods, *t*. However, the volumes harvested in adjacent periods are discounted. Heavy discounting leads to the stands only being counted as clustered if activities in geographically adjacent stands take place in the same period. In contrast, if the discounting is light, the period when the harvesting is done does not matter for it to be counted as clustered, as long as the harvest activities take place in adjacent stands.

The resulting two-objective problem was converted into a single-objective problem by weighting the two objectives together:

$$\text{Max Z} = w_1 \sum_{i=1}^{I} \sum_{j=1}^{J_i} D_{ij} X_{ij} + w_2 \sum_{i=1}^{I} \sum_{p=1}^{P} EV_{ip} \tag{3}$$

with weights w_1>0 and w_2>0 such that $w_1 + w_2 = 1$. D_{ij} denotes the NPV for stand *i* for treatment schedule *j* and X_{ij} is a binary variable indicating if stand *i* is assigned a treatment schedule j or not. To keep the harvested volume at a certain level a volume requirement for all periods was included in the model formulation.

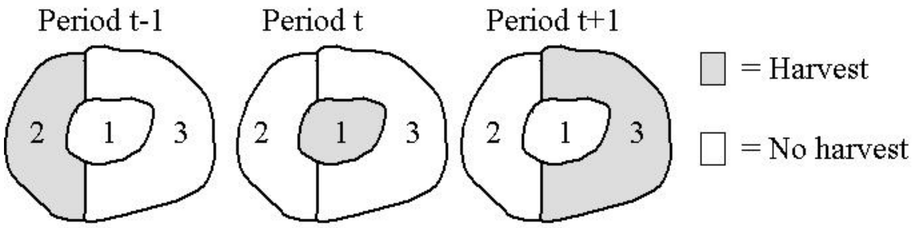

Figure 6. An example on the amount of effective volume in period t. The effective volume for stand 1 in period t is equal to the sum of the volume harvested in stand 1 period t, stand 2 period t-1 and stand 3 period t+1. However, the volume harvested in period t-1 and t+1 are discounted. For stand 2 and 3 the effective volume is 0 in period t since no harvest take place for those stands in period t

The presented model was applied in a case study to a landscape consisting of 2643 stands where substantial consideration was paid to other aspects related to biodiversity and recreation. The planning horizon was divided into 5-year periods, where the clustering requirements extended over the first 40 years. In the case study the presented problem was solved with SA. Using varying weightings for the NPV and effective volume generated a trade-off curve that was used for quantifying the trade-offs between the two goals. Sensitivity analyses were done to investigate the effects on the solutions of different discounting of the volume harvested in adjacent periods, *i.e.* the computation of EV. To evaluate if giving effective volume a high weighting generated a clustered layout of harvest activities the number of clusters produced in each period was counted.

The results from the case study indicated that the presented model is effective for clustering the harvest activities and that the clustering of the harvest is more pronounced later in the planning horizon, Fig. 7. This could be due to a number of factors. First, initial conditions give few possibilities to cluster the harvest in the beginning of the planning horizon, *i.e.* it takes several periods to create a spatial pattern. Second, young stands (which will be suitable for harvest in the future) are, on average, larger. This implies that in the future fewer but larger stands will need to be harvested to fulfill the harvest demands. Third, a certain amount of effective volume has the same value whether it is generated today or in the future. The results from the case study also indicated that it is possible to aggregate the harvest with only a small sacrifice of the NPV. Finally, the time required to solve the different combinations of the problem in the case study was short.

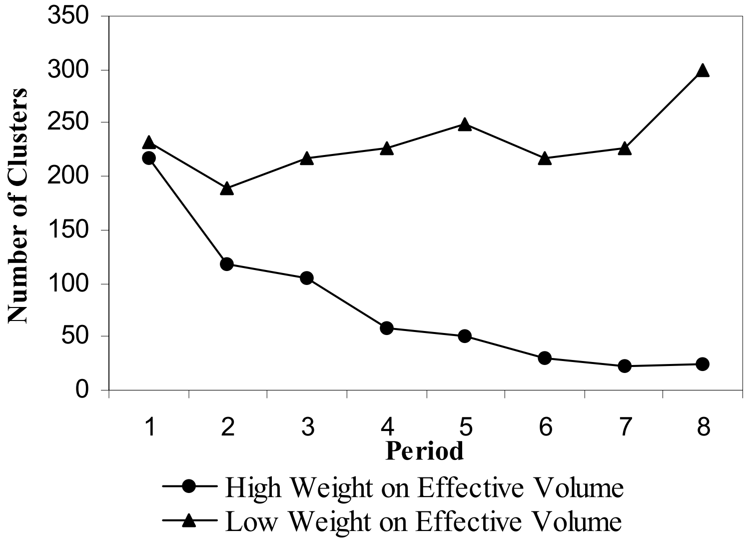

Figure 7. Comparison of the numbers of clusters in each period when the effective volume was given high and low weighting, respectively.

Paper V

In Paper V a new model for clustering harvest activities and areas set aside as reserves was presented. In contrast to Papers I-IV, the primary decision units in Paper V were pixels that were smaller than an ordinary treatment unit (20*20meters). The grid structure simplifies the neighborhood relationships in that a pixel is considered to have a maximum of four neighbors. This is exploited in this Paper by applying an exact solution method with integer variables.

The general planning problem in the Paper consisted of selecting pixels for management and among them selecting areas for final harvest in the first period so that the NPV over an infinite time horizon was maximized. The objective was restricted by the requirement that a certain volume should be harvested in the first period. A further restriction was that the pixels selected for harvest in the first period and those selected for the reserves, *i.e.* pixels not selected for management, should be clustered.

The criteria for aggregating pixels selected for harvest in the first period and pixels not selected for management at all were based on whether or not a pixel has interior conditions, Fig 8. A pixel, *i*, is defined as having interior conditions for harvest if it, and all the adjacent pixels, are selected for harvest in the first period. This condition is met in the presented model by demanding that:

$$C_i - X_l \leq 0, \ \forall i \in K, \forall l \in N^i \qquad (4)$$

where C_i is a binary variable indicating interior conditions for harvest for pixel i, X_l is the fraction of pixel l assigned to be harvested in period 1, K is the set of pixels that could have interior conditions and N^i is the set of pixels adjacent to pixel i (pixel i is also included in this set). Similarly, pixel i, is defined as acquiring interior conditions for reservation if it and all the adjacent pixels are not selected for management at all. This condition is met in the presented model by requiring that:

$$R_i + Y_l \leq 1, \ \forall i \in S, \forall l \in N^i \tag{5}$$

where R_i is a binary variable indicating interior conditions for reservation for pixel i, Y_l is the fraction of pixel l assigned to be managed and S is the set of pixels that could have interior conditions for reservation.

It should here be clear that it is not necessary to have integer restrictions on the X_i and Y_i since equation (4) force all X_l in the set N^i to be 1 if C_i is 1 and equation (5) force all Y_l in the set N^i to be 0 if R_i is 1.The two clustering requirements are then expressed in the model formulation by demanding a defined numbers of pixels with interior conditions for harvest and reserves.

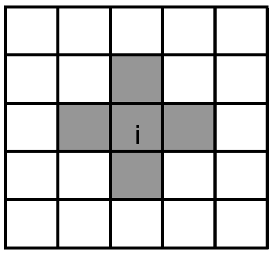

Figure 8. Pixel *i* get interior condition for harvest if pixel *i* and all edge adjacent pixels are harvested (=the shaded area). In similar way pixel *i* get interior condition for reserve if pixel *i* and all edge adjacent pixels are unmanaged and consists of old forest.

In a case study the model was examined using a data set consisting of 10 000 pixels. The model was solved by MIP with varying requirements for the number of pixels with interior conditions. The results indicated that the presented model is effective for clustering pixels selected for harvesting, Fig. 9. As the demand for pixels with interior conditions for harvest increased the degree of aggregation increased. Also, the pixels selected for reservation were clustered, Fig 9. When the demand for pixels with interior conditions for reserve was increased, more pixels became clustered around existing reserves, *i.e.* the degree of clustering did not increase. A promising result in Paper V was that despite the large number of constraints and variables it was possible to solve the MIP problem in a reasonable amount of time, *i.e.* the model formulation seems to be relatively integer friendly. The cost associated with clustering the harvest was modest in Paper V. The cost of clustering the reserves was more significant, but in the study both the spatial consideration and saving the old forest *per se*, contributed to the additional costs.

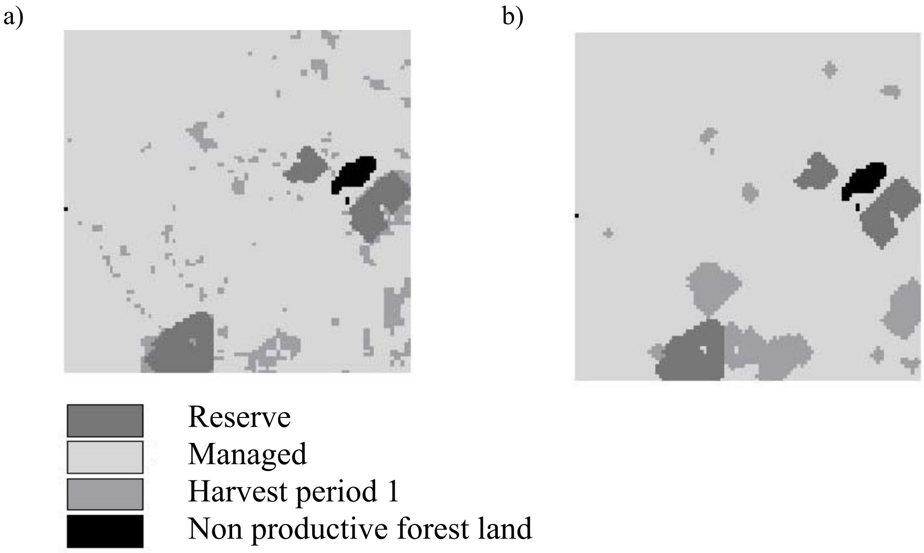

Figure 9. a) The spatial layout of harvests and reserves when no consideration was paid to the number of interior pixels harvested. b) The spatial layout of harvest and reserve areas when certain numbers of pixels with interior conditions were demanded for harvest and reservation.

Discussion

Analysis of the main results

In this thesis, different approaches for including consideration of spatial relationships in forest planning have been examined. A number of criteria for expressing spatial relationships between planning units were investigated. The criteria were all designed to create connectivity in terms of contiguous areas of old forest or contiguous areas of harvest activities while meeting other goals, such as maximizing the NPV. Both heuristic methods and exact solution techniques were used for solving the ensuing management problems. In addition, both pixel and stand-based approaches were tested. Emphasis was put on problems reflecting real-life situations. There are, of course, a number of spatial aspects that is not covered by the thesis. Still, the results from these studies could hopefully be used for indicating how other spatial issues could be included in long-term forest planning.

While Papers I, II and IV only used SA for solving the stated management problems, in Paper III the heuristic method was combined with LP into an integrated solution process. The SA algorithm used in Papers I, II and IV seemed to work well in terms of finding near-optimal solutions. However, when more forest-wide constraints were added, as in Paper III, the SA algorithm was more inclined to get stuck at local optima. Better solutions could probably have been found with better parameter settings. However, an important issue that should be considered when evaluating any solution method is the intrinsic difficulty of handling it. In contrast to the other studies an exact solution technique, MIP, was used in Paper V. An exact technique has several advantages. First, it provides an optimal solution. Second an exact method could be used for evaluating solutions provided by heuristic methods. However, in Paper V several simplifications were applied. For example, the cluster requirements for harvest were only valid in the first planning period. More research is therefore needed to investigate the effects on the efficiency of the solution methods of extending the problem.

Although it is not possible to compare solution times between different problems, some general findings can be discussed. The choice of criteria, the selected solution technique and of course the scale of the problems in terms of the number of variables and constraints involved all affect the solution times for a given problem. To avoid solution times becoming unnecessarily prolonged, it is important that the selected criteria are computationally well behaved so they can then be efficiently included in optimization models. When a solution is changed by, for instance, adjusting the treatment for a single stand, it should be possible to recalculate the amount of the selected criteria for only the changed stand and its neighbors. This applies to all the criteria used in the thesis. Further, the results from Paper III indicate that one way to shorten the solution time is to combine two different methods into one integrated solution process instead of solving the whole problem with a heuristic method. The spatial part of the problem can then be solved with a heuristic method while the forest-wide non-spatial part of the problem is solved with LP.

Just as it is not possible to directly compare the solution times, it is not possible to compare the cost of including spatial considerations between different problems since the cost is always situation specific and connected to the planning case's objectives, constraints and the structure of the forests. However, overall, the results from the different papers suggest that the cost of aggregating the harvest activities is low. This could be because the losses in the NPV incurred by moving the harvest one period backward or forward are low, *i.e.* the curve for the optimal harvest period is smooth. Furthermore, the decrease in the NPV could be partially compensated by the savings accruing from, *e.g.* reductions in road building and the movement of machines between stands, aspects not explicitly accounted for in the models. The cost for creating contiguous areas of old forest seems to be more significant. However, it is difficult here to draw general conclusions since these costs are due both to including spatial considerations and to saving the old forest *per se*. The cost is also highly influenced by the definition of old forest and the initial conditions in the landscape, as illustrated in Papers I and II. Furthermore, the estimation of the cost involved in taking spatial considerations into account, regardless of whether it is done to create contiguous areas of old forest or to aggregate the harvest, is also affected by the solution method. Problems without spatial consideration could often be solved with exact solution techniques, while spatial problems are often solved with heuristic methods and consequently optimality is not guaranteed.

Conclusions

In conclusion, it appears possible to include considerations of spatial relationships in long-term forest planning also when the problems are of a size found in real-world situations. However, approaches other than traditional methods, are often needed. For problems where the forest-wide constraints are few and only relate to the spatial aspects it would seem that heuristics alone is adequate. When more forest-wide constraints are added to the problem a suitable approach could be to combine two-solution techniques into a single-solution procedure, such as SA and LP. Another way to approach the problem is to work with exact solution methods. The experiments with MIP models suggest that, at least when pixels are used as the primary decision unit, also relatively large problems can be solved exactly if proper formulations can be found. Finally, from a practical point of view it seems that using effective methods for solving spatial problems will reduce the cost connected to taking spatial considerations.

Future research

There has been extensive research into spatial problem solving during the last ten years or so. However, the research has failed to address issues of practical value for forestry in at least two ways. First, a majority of the studies deal with the problem of how to avoid harvesting adjacent areas, whereas only a small number deal with problems such as planning management activities while avoiding fragmentation or creating corridors between valuable habitats. Second, there has been no systematic appraisal of solution methods of the different kinds of problems that have been explored. This has two adverse implications for practical implementation of the results. The first is that there is, as yet, no way of characterising a new problem in terms of its suitability for a specific solution method. The other is that, in the absence of a taxonomy of some sort, each case study represents a unique event. There is, in other words, an almost complete lack of benchmarking. Such benchmarking is essential to allow methods to be selected that give forest managers the best possible solutions in the time available for solving particular problems.

A future research objective proceeding from these studies could therefore be to develop a taxonomy that could be used for finding a suitable solution method for an arbitrary problem. This characterization should be based on the structural features of the problem, *i.e.* those characteristics that decide how difficult it is to solve a spatial problem and what method could be best employed to tackle it. Parallel to this work, different solution techniques would be evaluated for the different types of problems.

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Now, this thesis is finished. Sunday, 05 August 2001, 9:47