# Spatial Problems in Long-Term Forest Planning

## From Preferences to Plans


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# Spatial Problems in Long-Term Forest Planning. From Preferences to Plans


## Abstract

In modern forest planning, it is important to account for the value of timber production and for other values of the forest. Important factors such as the protection of biodiversity, recreational use and traditional uses of forests are often connected to specific places in forests, or to the spatial structure of the forests. Moreover, the worth of these factors is often difficult to express in objective terms because they are usually valued based on individual preferences or subjective evaluations of complex situations. The objective of this thesis is to analyze specific issues relating to spatial preferences and test approaches that can be used to value them more accurately in forest planning processes.

The individual studies appended to this thesis approach spatial preferences from different perspectives. Paper I identifies some difficulties associated with the consideration of spatial preferences in forest planning processes. Paper II describes the development and testing of a method for eliciting spatial preferences. Papers III and IV concentrate on the design and evaluation of forest plans that account for spatial considerations. In Paper III, different fragmentation indices were used to simulate changes in the distribution of different stand types within a forested region over time. Paper IV uses existing information on the requirements of reindeer husbandry concerning forest management practices to evaluate the consequences of adopting different forest management regimes for reindeer husbandry.

The results highlight the importance of being careful when eliciting preferences. Particularly when dealing with spatial preferences, where it can be difficult to accurately represent objectives in numerical terms, oversimplification and misinterpretation of preferences can result in the production of plans with undesirable outcomes. The case studies examined in this thesis provide insights to the tradeoffs that must be made between different objectives. The results presented herein should be useful in increasing the efficiency of the planning process in order to ensure that the selected plans match the decision maker's preferences as closely as possible.



*Keywords:* fragmentation, multi-objective forestry, place-specific values, preference elicitation, reindeer husbandry, spatial forest planning, value function



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*To live is to choose. But to choose well, you must know who you are and what you stand for, where you want to go and why you want to get there.*

Kofi Annan

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# List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Korosuo, A., Wikström, P., Öhman, K. & Eriksson, L.O. (2011) An integrated MCDA software application for forest planning: a case study in southwestern Sweden. *Mathematical and Computational Forestry & Natural-Resource Sciences (MCFNS)* 3(2), 75-86. Available in http://mcfns.com/index.php/Journal/article/view/88

II Korosuo, A., Holmström, H., Öhman, K. & Eriksson, L.O. (2013). Using value functions to elicit spatial preference information. *European Journal of Forest Research* 132 (3), 551-563.

III Korosuo, A., Heinonen, T., Öhman, K., Holmström, H. & Eriksson, L.O. Spatial optimization in forest planning using different fragmentation measures (submitted manuscript).

IV Korosuo, A., Sandström, P., Öhman, K. & Eriksson, L.O. Impacts of different forest management scenarios on forestry and reindeer husbandry (submitted manuscript).

Papers I and II are reproduced with the permission of the publishers.

Author contributions:

I AK, OE and KÖ planned the study. Prior to the study, AK made tests with PlanEval, and PW made changes to the software according to suggestions. AK and OE performed the interviews. PeWi, OE and AK formulated and simulated the plan alternatives. AK analyzed the results and wrote the major part of the manuscript. All co-authors contributed with comments to writing.

II AK, HH and OE initiated the study. AK, OE and KÖ planned the value functions approach. HH formulated the plan alternatives together with AK. AK carried out the data collection and analysis and wrote the manuscript. All co-authors contributed with comments to writing.

III AK, KÖ and OE planned the study. TH formulated the models. AK and TH solved the planning problems and analyzed the results. AK wrote the major part of the manuscript, with comments and text from all co-authors.

IV PS and AK conceived the study. AK, OE and KÖ planned the problem formulations. AK and OE formulated the planning models and AK simulated the scenarios and analyzed the results. AK wrote the major part of the manuscript, with all co-authors contributing with comments and text to writing.

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# Abbreviations

| | |
|---|---|
| ADJ | Adjusted scenario |
| AHP | Analytic hierarchy process |
| AvgArea | Average area of patches |
| BAU | Business as usual scenario |
| BL | Broad-leaf (data) |
| CCF | Continuous cover forestry |
| DM | Decision maker |
| dNN | Mean distance between neighboring patches |
| DSS | Decision support system |
| MAUT | Multi-attribute utility theory |
| MAVT | Multi-attribute value theory |
| MCDA | Multi-criteria decision analysis |
| NPV | Net present value (In paper IV: Net present value -maximizing scenario) |
| Nr | Number of patches |
| SA | Simulated annealing |
| SDSS | Spatial decision support system |
| SI | Shape index |
| SMART | Simple multi-attribute rating technique |

# 1 Introduction

## 1.1 Forest planning in the context of decision making theory

Most of Sweden's forests are privately owned and managed for timber production (Skogsstyrelsen, 2013; SLU, 2012). Non-industrial private forest owners own half of the country's 23 million hectares of productive forest land, while forest companies own another 25% of the total. The Swedish forests play a vital role in maintaining and enhancing biodiversity (Larsson & Danell, 2001; Angelstam & Pettersson, 1997). Thanks to the concept of every man's rights, recreational uses of forests, such as camping, fishing, hiking and berry and mushroom picking, are popular and are commonly performed in both privately and publically owned forests (Bolund & Hunhammar, 1999; Lindhagen, 1996; Bostedt & Mattsson, 1995). In northern Sweden, forests also accommodate reindeer husbandry that provides the traditional livelihood of the indigenous Sami people (Berg *et al.*, 2008; Danell, 2000). Thus, while forests are primarily valued economically for their timber output, most forests also provide a diverse range of ecosystem services. In recent decades, greater emphasis has been placed on the value of these other uses and ecosystem services during the forest planning process.

Forest planning is the field of study that investigates the desires of different individuals and groups concerning forest use, models future scenarios based on different forest management options, and analyzes potential outcomes with respect to the defined objectives. In long-term forest planning, the planning horizon usually extends over at least one complete rotation period. It can be regarded as a form of scenario analysis in which one simulates a series of potential development pathways for the forest, thereby enabling the evaluation of different strategic decisions. Most of the problems in forest planning also have spatial dimensions, in that the locations at which the management actions are performed will influence their results. Consequently, the three main questions asked in forest planning exercises are: "What should we do, when should we do it, and where should it be done?"

Forest planning has its theoretical basis in general decision-making theories that were developed to analyze the structure of decisions and the process of decision-making. Multiple models of the decision-making process have been developed, which typically describe it in terms of three separate processes: the identification of the problem, the development of one or several possible solutions, and the selection of the best of these solutions (Gregory *et al.*, 2012; Mintzberg *et al.*, 1976; Simon, 1960; Dewey, 1933). The term "planning" encompasses activities in all three stages. Some models also include the implementation of the plan as a fourth stage in the process, but that is not the case in this thesis.

Forest planning processes usually involve two actors: the decision maker (DM) and the analyst. These terms refer to the roles of the actors in the planning process, and not necessarily to two different individuals. In private forestry, the DM role is usually played by the forest owner. The analyst could be a forest planning expert who offers technical and factual advice during the planning process (Belton & Hodgkin, 1999). In this thesis, the terms *planning process* and *decision-making process* are used interchangeably, although they have slightly different connotations. In a planning process, the focus is on structuring and formulating the problem and it is assumed that the planner has no personal stake in the decisions made or bias towards any particular set of values. Conversely, in a decision-making process, there is a greater emphasis on the perspective of the decision maker, who will focus on the impact of the available options and the outcome of the process. Thus, discussions of the planning process focus on the role of the analyst, whereas the decision-making process has more to do with the role of the DM. In addition to the DM and the analyst, there may also be other actors involved in a planning process. Experts can provide additional knowledge regarding specific aspects of the planning problem. For example, remote sensing and inventory experts can be a vital source of data on the state of the forest. In some situations, especially when planning forests located near towns and other places of public interest, the planning process may also involve the stakeholders, who participate in the planning process but do not have a mandate to make the final decisions (Reed, 2008).

In the context of decision-making theory, the word "*problem*" does not have the negative connotation it often carries in every-day life. Instead, in a decision making process, a problem represents an opportunity to change the current situation (Keeney, 1992). For a problem to be meaningful in the context of decision-making, there must be multiple means by which it could possibly be addressed, and these alternatives need to be of different value to the DM. Keeney (1992) distinguishes between alternative-driven and value-driven decision processes. In an alternative-driven process, one begins by defining the available options and then chooses between them on the basis of the DM's values and preferences. In a value-driven process, one begins by specifying the DM's values and then designs potential solutions based on those values.

The decision objects in forest planning have traditionally been the forest stands. A forest stand is a contiguous area containing trees that are similar enough to be treated simultaneously. The timing of the harvests and other forest management operations are selected based on information about stand characteristics, such as the age, size and number of trees within the stand, as well as the type of vegetation present and the properties of the soil. Because several treatment schedules can generally be applied to any given stand, the number of management options available for the forest as a whole is usually extremely large. The planning problem is therefore usually formulated as an optimization problem in which the objective is to maximize the economic value of the harvests. The importance of other uses of the forest can be accounted for in various ways. For example, one might impose constraints on the harvesting of specific stand types or require that a certain proportion of the forest be allowed to grow without disturbance. In Sweden, forest management must be done in accordance with the concepts of sustainable forestry as outlined by the Forestry Act and the certification requirements of the Forest Stewardship Council (FSC, 2013; Skogsstyrelsen, 2013). In recent years, techniques have been developed that make it possible to account for the value of factors and ecosystem services other than timber production in the planning process (Öhman *et al.*, 2011; Hurme *et al.*, 2007; Kangas & Kangas, 2005; Kajanus *et al.*, 2004; Kurttila & Pukkala, 2003; Pukkala *et al.*, 1995). The value of these factors and services is often associated with specific locations within forests or the spatial structure of the forest as a whole. Such values are often difficult or impossible to express in objective terms because they are highly dependent on the subjective preferences of the DM.

## 1.2 What is a preference?

### 1.2.1 Terminology

The *preference* of the DM is defined in this thesis as the answer to the question "What does the DM want?" It is closely associated with the existence of alternatives: "I prefer A to B" is a vocal expression of the valuation of A over B (Bogetoft & Pruzan, 1997). The concept of preferences has roots in different disciplines, and is used in fields such as cognitive psychology (Lichtenstein & Slovic, 2006), behavioral science (Keeney & Raiffa, 1993), and economics (Beshears *et al.*, 2008). In forest planning, an understanding of the DM's preferences is essential when determining whether a given management option will satisfy their wants.

Several different terms are used in the literature when discussing preferences. Some of these are used interchangeably but in some cases they refer to slightly different aspects of the decision problem:

- *Value* is usually used to describe a person's ethical principles, the more fundamental guidelines and priorities they follow (Bogetoft & Pruzan, 1997; Keeney, 1992). According to Keeney (1992), "thinking about values is constraint-free thinking", which means that values are underlying characteristics that the individual holds even in the absence of a decision problem.
- A *criterion* is a standard of judgment that can be used to evaluate or rank the various available options (Geneletti, 2004; Malczewski, 1999; Bogetoft & Pruzan, 1997). "Criterion" is a generic term that encompasses two key concepts: *objectives* and *attributes*.
- *Objective* is often used interchangeably with *goal* and refers to something one intends to accomplish through a planning process (Bogetoft & Pruzan, 1997). In the context of decision making, goals and objectives are used to define a direction of preference relative to a given object. Keeney (1992) distinguishes between these two terms, using "objective" to describe more generalized desires (e.g. "maximize safety"), whereas "goals" are more specific (e.g. "ensure that there are zero accidents").
- *Attributes, factors* and *indicators* are measurable quantities or parameters that are used to determine the degree to which an objective has been achieved (Geneletti, 2004; Malczewski, 1999). Keeney (1992) divides these concepts further into *natural attributes* (which can be evaluated using pre-existing scales), *constructed attributes* (that are evaluated against subjective scales), and *proxy attributes* (attributes that are evaluated indirectly by reference to a different but related attribute).

In addition to these expressions of preference, a decision-making situation will typically involve the establishment of a series of *alternatives* (a set of possibilities available to a DM), a *decision* (the selection of an alternative), and *action* (the implementation of the chosen alternative) (Bogetoft & Pruzan, 1997).

Depending on the definition used, one might consider preferences to be revealed during the decision-making process, or constructed during the process. Lichtenstein and Slovic (2006) suggest that the construction of preferences is more plausible than revelation, especially in situations where the decision object is unfamiliar or complex. In contrast, Beshears et al. (2008) argue that underlying preferences are revealed rather than constructed, but distinguish between the stated and normative preferences. These terms, which are often used in economic valuation studies, refer to the difference between how people really feel (normative preferences), how they describe their preferences beforehand (stated preferences), and how they actually choose their actions (revealed preferences).

### 1.2.2 Spatial preferences

Decision problems can be said to have a spatial character if they involve geographical data or are otherwise are associated with a place or location (Malczewski, 1999; Aronoff, 1989). This broad description covers a wide range of planning problem types, some of which are more common in forest planning situations than others.

Van Herwijnen (1999) has described different problems and objectives that can be associated with spatial preferences in different situations. These include *site selection problems*, which are typically associated with decisions regarding the location of a facility or a park (e.g. Geneletti & van Duren, 2008; Zucca *et al.*, 2008); *spatial objectives*, which relate to the size, shape, contiguity or compactness of a landscape; and *non-spatial objectives*, i.e. objectives that cannot be classified as spatial objectives but for which spatial data must be considered when determining whether the objective has been attained. Malczewski (1999) describes spatial and non-spatial objectives in terms of *explicitly* and *implicitly spatial objectives*. He also adds the concepts of *implicitly and explicitly spatial alternatives,* where explicitly spatial alternatives include things such as potential solutions to the site selection problems described above. In contrast, implicitly spatial alternatives are non-spatial alternatives that have a spatial impact. For example, the decision problem may involve the creation of a system for controlling flooding within a given area, in which case the available options will not themselves be spatial but the selection of a specific option will have an effect on the landscape.

The various elements of spatial decision-making problems described above are applied relatively widely in different environmental decision making problems, especially in the selection of reserve sites (e.g. Snyder *et al.*, 2004). However, forest planning involving spatial phenomena has a slightly different starting point. In a forest planning problem, the location of each stand is known beforehand, and the decision problem involves finding a suitable use for each "location" on the map. Nordström et al. (2011) attempted to structure the spatial values involved in forest planning situations by dividing spatial values into *place-specific* and *nonplace-specific* values. In this context, place-specific values are associated with areas that are important because of their location, often in combination with certain landscape structures or other spatial attributes of the forest. These places are not interchangeable, which means that a loss of one such area cannot be compensated by preserving another area. Areas of this type are often associated with strong personal opinions and preferences, as described by Kangas et al. (2008). In contrast, the nonplace-specific values described by Nordström et al. (2011) resemble the explicitly spatial criteria and objectives introduced previously, describing the certain spatial conditions required for the stands. In contrast to the place-specific areas, the loss or removal of an area that has only nonplace-specific value can be fully compensated by preserving or adding a similar area in a different location.

### 1.2.3 How are preferences elicited?

Elicitation of preferences refers to the quantification of the DM's values and criteria regarding a decision problem. The aim is to simplify complex judgments into objectives and attributes that can then be used to formulate and evaluate different decision alternatives.

In forestry, the traditional focus on economic profits did not explicitly require a formal value elicitation process: it was generally assumed that the DM's objective was to maximize the economic profit gained from the forest. The inclusion of additional objectives in the formal planning process introduces the problem of assessing their relative importance. It can be difficult to accurately compare the value of biodiversity, recreational uses, and the preservation of local traditions to that of timber harvest volumes and monetary profits. In economics research, a range of different contingent valuation methods, such as willingness to pay, have been used to assign a monetary value to factors of this type (Lichtenstein & Slovic, 2006). These methods provide readily comparable data on relative preferences. On the other hand, they may be inaccurate and there may be large discrepancies between the stated and revealed preferences, because in many cases there is no direct correspondence between these factors and monetary value (Beshears *et al.*, 2008; Champ *et al.*, 2003).

Another approach that is used to elicit and compare different types of preferences is multi-criteria decision analysis (MCDA) (Kangas & Kangas, 2005; Belton & Stewart, 2002; Malczewski, 1999). MCDA is an umbrella term that encompasses several different methods for structuring and solving decision problems that depend on different types of criteria. The underlying idea behind MCDA is that different types of objectives do no need to be expressed in similar units, but instead can be compared in their own terms. Most of the preference elicitation methods used within MCDA are based on the multi-attribute utility or value theory (MAUT or MAVT) (Keeney & Raiffa, 1993). In this context, utility refers to a decision situation that accounts for risks, whereas value does not include a risk factor. In MAUT/MAVT, each objective is first expressed in terms of its utility to the DM, after which the total utility of the decision alternative with respect to the objectives can be computed. Value or utility functions may be formulated in order to illustrate the objectives and simplify their formulation (Beinat, 1997). Methods that use the MAUT concept include analytic hierarchy process (AHP), inverse preference methods, outranking, and goal programming. A central feature of the MCDA approaches is that they treat the structuring of the problem, the identification of the DM's preferences, and the analysis of the trade-offs associated with the different alternatives as important outcomes in their own right, along with the final decision itself (Belton & Stewart, 2002).

## 1.3 Spatial forest planning

The focus of forest planning is continually being expanded in order to more fully account for the value of ecological and social factors alongside traditional economic goals. This expanded focus has also lead to an expansion of the spatial scale of planning: in addition to plans on the level of the forest estate, there is growing interest in landscape-level objectives and consequences (Kurttila, 2001; Baskent, 1999). Spatial forest planning is a generic term that refers to forest planning studies in which there is a particular emphasis on spatial problems (see Baskent & Keles, 2005 for an overview). In forest planning calculations, the term "planning problem" usually has a more narrow meaning than in general decision theory. Specifically, the problem in this context is the formulation of an appropriate optimization algorithm.

When formulating spatial forest planning problems, spatial preferences are accounted for in either an exogenous or endogenous manner (Öhman & Eriksson, 2002; Kurttila, 2001). In the exogenous formulation, spatial factors such as specific locations are analyzed separately from the other planning units, before the optimization is conducted. The rest of the planning problem is then solved without considering spatial factors, often using linear programming. A typical example of such a formulation is the delineation of stands including key biotopes or riparian zones around bodies of water, and assigning them no management operations. In endogenous approaches, the spatial criteria form part of the optimization problem. Endogenous problem models are usually nonlinear and require integer solutions. They are therefore usually solved using optimization methods such as mixed integer programming or heuristic algorithms (Öhman & Wikström, 2008; Pukkala & Heinonen, 2006; Pukkala & Kurttila, 2005; Bettinger & Sessions, 2003; Bettinger *et al.*, 2002). Kurttila (2001) divides endogenous approaches into three categories: those based on adjacency constraints, species-specific approaches, and landscape-level approaches. Adjacency constraints are particularly common in North America, where the green-up constraints regulate the simultaneous harvesting of neighboring stands (Murray & Weintraub, 2002). Species-specific approaches are concerned with preserving the habitats of certain species. In problem formulations of this type, the specific needs of each species of concern are described and incorporated into the planning problem (Öhman *et al.*, 2011; Hurme *et al.*, 2007; Edenius & Mikusiński, 2006; MacMillan & Marshall, 2004; Store & Jokimäki, 2003; Kurttila *et al.*, 2002). Methods of the third kind, i.e. landscape-level approaches, incorporate spatial preferences into the planning problem as either landscape- or patch-level indices. Patch-level indices such as measures of patch size and shape, core area or distance to the nearest neighboring patch can be regarded as patch-level goals, or aggregated and analyzed at the landscape level as measures of landscape composition or configuration (Long *et al.*, 2010; Venema *et al.*, 2005; Fahrig, 2003; Geoghegan *et al.*, 1997; Baskent & Jordan, 1996; Pukkala *et al.*, 1995).

Much research has been devoted to structuring and solving spatial forest planning problems. However, most of studies in this area assume that the decision makers' preferences with respect to each relevant criterion are perfectly known. Moreover, they usually attempt to either maximize or minimize the spatial variables involved, assuming a monotone pattern in the preferences associated with the variables. In reality, the preferred level of the landscape structure may lie somewhere in between these extremes. More sophisticated analyses of preferences, especially those that are tied to specific locations or landscape patterns, are not yet very common in forest planning situations. Such analyses could be useful both in helping the DM to identify their wants and wishes regarding forests and their use, and also in guiding the process towards a plan that reflects these preferences more fully.

# 2 Objectives

The objective of this thesis is to investigate how spatial preferences can be used to design forest planning options and used in the evaluation of the resulting plans. In the thesis, I test different approaches for eliciting and applying spatial preferences within forest planning, and evaluate the criteria and indicators used to describe the resulting plans. The thesis is based on four case studies, all of which involve multiple objectives within forest planning problems.

Paper I covers all the phases of the planning process, from problem formulation to the choice of the plan, in a multi-criteria situation. Papers II and III describe different aspects of the planning process in a project whose aim was to incorporate biodiversity objectives into long-term forest planning. Paper II focuses on the elicitation of preferences concerning landscape structure and the conversion of these revealed preferences into measures that can be used in forest planning calculations. Paper III analyzes these measures as spatial objectives in forest planning, and investigates the effects of the chosen measures on the resulting landscape and forest plans. Paper IV presents different forest management scenarios and analyses their structural, spatial and temporal characteristics in terms of reindeer husbandry.

The findings from these studies provide insights into the methodological issues involved when attempting to explicitly consider spatial problems in forest planning. The case studies presented in this thesis also provide a glimpse into some spatial problems that are commonly encountered in Swedish forestry, and describe methods that could be used to account for them in long-term forest planning.

The specific objectives of the papers included in this thesis were:

Paper I: To investigate the preferences of the manager of a larger non-industrial forest estate and structure them in a formal MCDA process. Also, to assess the strengths and weaknesses of the newly developed decision support tool when comparing and choosing between long-term forest plans.

Paper II: To explore a method for eliciting preferences concerning landscape structure and translating the revealed preferences into value functions based on numerical landscape indices.

Paper III: To evaluate the landscape effects associated with the use of different fragmentation indices in long-term forest planning, and to compare the performance of the different indices.

Paper IV: To define measures for assessing the effects of different forest management plans on reindeer husbandry conditions, formulate different scenarios and evaluate their impact on reindeer husbandry in the landscape and over time.

# 3 Materials and methods

## 3.1 An integrated MCDA software application for forest planning: a case study in southwestern Sweden (Paper I)

The objective of this study was to test the newly developed MCDA software package PlanEval in a real planning situation, and to evaluate the benefits and drawbacks of using such a tool. This was done as a case study on a 2 930 ha forest estate in Southwestern Sweden. The DM role in this case was played by the forest manager, with the assistance of a forestry consultant.

The paper describes the phases of the planning process, which was conducted according to the Intelligence-Design-Choice system of Simon (1960). In the intelligence phase, existing forest data were acquired and the DM's objectives and sub-objectives in forest management were mapped via a series of discussions conducted via mail and in person. Laminated thematic maps were used to identify the spatial objectives involved, and potential locations of such objectives were marked on the maps. The discussions resulted in the specification of objectives concerning timber production, nature conservation, recreation, water quality protection, and the maintenance of certain forestry traditions on the estate (see Table 1 in Paper 1). The spatial objectives revealed in the discussions included the establishment of buffer zones for water bodies, the protection of certain known locations of osprey (*Pandion haliaetus*) nests, and a wish to prevent simultaneous harvesting on both sides of paths and streams used for recreational purposes.

In the design phase, the objectives identified in the intelligence phase were used to prepare three planning alternatives using the PlanWise planning system. Place-specific values (buffer zones around water bodies, osprey nests, key biotopes) were delineated to allow for undisturbed growth. Different priorities were placed on the other objectives that were amenable to simulation with the planning tool in the three different plans; thus, plan A emphasized timber production, plan B focused on conservation, and plan C focused on the recreational uses of the forest.

In the choice phase, we met with the DM again and introduced him to the forest plans and the PlanEval software. The concept of MCDA was briefly explained to the DM, and the plans were described in brief. A draft objective hierarchy for use in PlanEval was presented, discussed with the DM and adjusted slightly based on issues that came up during the discussion. Once this had been done, the DM evaluated the plans by conducting an analytic hierarchy process (AHP) analysis using PlanEval, with the authors' assistance.

## 3.2 Using value functions to elicit spatial preference information (Paper II)

This paper presents a method for eliciting preferences concerning landscape structure by using value functions. The paper is based on a case study that was conducted in the context of a project whose aim was to assess the value of the biodiversity within a forested landscape in Vindeln, Northern Sweden. Two different scenarios were considered in order to investigate the scope for increasing the number of broadleaf trees in the landscape. Broadleaf-rich stands are disfavored under the current forest management regime, but are important for many species that often have quite different habitat requirements. In this paper, we defined a forest stand as a patch or part of a patch if broadleaf trees (birch and aspen) accounted for more than 20 % of the stand volume and the mean stand age was greater than 50 years.

The method presented in the paper is based on four steps:

1. Thematic maps showing different spatial patterns are prepared.
2. These maps are evaluated by assigning points: the most-preferred map is assigned 100 points, and the rest of the maps are assigned between 0 and 100 points, relative to the most-preferred map.
3. Descriptive indices are calculated for the maps.
4. The map evaluations and the fragmentation indices are then combined to form a value function.

In the first step, five maps showing the whole area (large-area maps), and five maps showing zoomed-in parts of the map (small-area maps) were prepared. Each map had a different visual pattern of broadleaf-rich stands, ranging from very clustered patterns to very dispersed. They were colored in two shades of green, with light green areas representing broadleaf-rich stands and dark green areas representing conifer stands. The total area of broadleaf-rich stands was the same in all maps (15 % of the total area).

In the second step of the method we used the Simple Multi-Attribute Rating Technique (SMART) (von Winterfeldt & Edwards, 1986) to assess the value assigned to each map. This method was chosen largely because of its simplicity. However, it is possible that other value elicitation methods would have been equally viable. In this step, the ten respondents all assigned points to both the large-area and small-area maps, which were printed on A4 sheets. In addition to point allocation, the respondents were allowed to write notes on these sheets. The respondents were instructed to use their personal judgment when evaluating the maps, and to make it clear if they had placed particular emphasis on the needs of a given species when conducting their evaluations. Two respondents based their evaluations on the needs of woodpeckers (*Dendrocopos leucotos* and *Dendrocopos minor*), whereas the other eight focused on the landscape as a whole, considering the needs of multiple species.

In the third step of the method, different landscape indices were calculated for the study area. The chosen indices were mean patch size, number of patches, mean distance to nearest neighboring patch and shape index. These indices were selected to provide an overview of different aspects of forest fragmentation (see e.g. Fahrig, 2003 for an ecological analysis of the different measures).

In the fourth and final step, the evaluations of the reference group were sketched against the maps based on the four landscape indices. Value functions were drawn up for each individual respondent and their evaluations of both the large-scale and the small-scale maps.

## 3.3 Spatial optimization in forest planning using different fragmentation measures (Paper III)

This paper deals with the planning problem introduced in Paper II, and compares the landscapes that result from the different plans, using the various landscape indices as objectives in a long-term forest planning problem. The indices used to describe the spatial objective of minimizing fragmentation were the number of patches (Nr), the average patch area (AvgArea), the distance between the nearest neighboring patches (dNN) and the shape index (SI). These indices were used to establish forest planning problems that simulated the development of the landscape's structure over a 100-year planning horizon and allowing for dynamic patch construction. In addition, the planning problem was also solved to maximize the net present value (NPV) of the timber produced and the total area of habitat for various species of interest. All of the objectives other than NPV were evaluated based on the average values of the patches in the landscape over the planning period as a whole. In addition to the six spatial and non-spatial objectives, a demand for a constant level of harvesting was incorporated into the problem's formulation.

The planning problems were solved for two different data sets, business as usual (BAU) having a smaller amount of management alternatives available that could develop into broadleaf-rich patches than the broadleaf-simulating data (BL). The problems were formulated to maximize the subutility function associated with each objective, one at a time, together with harvest objectives that were included to maintain a constant harvest volume over the planning horizon. The problem was solved using the simulated annealing (SA) heuristic method. The preference information presented in Paper II was not used in this work; instead, the problem was approached from a more traditional perspective with the aim of minimizing landscape fragmentation.

## 3.4 Impacts of different forest management scenarios on forestry and reindeer husbandry (Paper IV)

This study was based on simulations conducted to predict the outcomes of scenarios involving three different management regimes for a forested reindeer husbandry area in northern Sweden. The first simulation focused on a "business as usual" (BAU) scenario in which it was assumed that the current management practices would be retained. In particular, it was assumed that there would be no pre-commercial thinning of the stands within the studied area. In the second scenario (ADJ), pre-commercial thinnings were required for all stands and the regeneration of lodgepole pine was prohibited, in keeping with the requirements of reindeer husbandry. In addition, the simulation assumed that even-aged management based on continuous cover forestry (CCF) would be implemented where economically viable. The third scenario was designed to reflect the management regime that might be implemented by a forest company that was seeking to maximize the net present value (NPV) of the forest. Two areas with different lichen conditions within the typical winter grazing lands of the reindeer herding community were considered in each simulation. The aim of the study was to define criteria for measuring the amount of viable reindeer pasture land in each scenario and to evaluate the different scenarios based on these criteria and on conventional forest management objectives.

The availability of reindeer winter pasture was evaluated in terms of the total area of reindeer pasture, which was divided into primary pasture and secondary pasture. These areas were further divided into stands with forest canopy cover and open areas. The possibilities for pasture were estimated based on the presence of vegetation types that facilitate the growth of ground lichens, which are the most important sources of reindeer fodder during the winter months. For a site to be classified as primary or secondary pasture, it had to exhibit specific properties. In particular, it had to either be an area of open space with a stand height of less than 3 m or have a sparse forest canopy cover with a basal area of less than 20 $m^2ha^{-1}$ and fewer than 1600 stems $ha^{-1}$.

# 4 Results

The results presented in Paper I revealed that the preferences stated during the intelligence phase did not completely match those revealed during the choice phase. During the intelligence phase of this study, the objectives were mapped so thoroughly that there was little room to prepare a set of widely divergent alternative plans. However, during the choice phase, the DM clearly focused on the plan that maximized the economic value of the forest, even though this was only one element among many in the initial set of objectives and all of the suggested plans were relatively similar with respect to this objective.

The MCDA method used in Paper I proved to be a somewhat cumbersome tool for comparing the available planning options. Even though the objective hierarchy used in this study was not very extensive, it still required 31 different pairwise comparisons. The novelty of PlanEval lies in its access to the data behind the alternative plans, which could potentially allow the decision maker to analyze the data from multiple perspectives and thereby conduct a more thorough assessment of the resulting landscapes. However, these features were not well exploited in this case study, partly because switching from one view of the data to another proved to be difficult for a user who was unfamiliar with the software, and partly because of pure exhaustion on the DM's part when confronted with such a wide range of different comparisons. This problem became especially pronounced when analyzing maps, where it became difficult to make meaningful comparisons if the objects considered were too small, but the cognitive demands involved in constantly zooming in and out and evaluating changes over different periods of time became excessively burdensome. On the other hand, the process did clarify the preferences of the DM regarding the forest property. The analysis clearly revealed the trade-offs associated with different plans that were put forward, and thereby provided useful information for future decisions concerning the forest's management.

The results presented in Paper II illustrate the connection between statements of individual preference and landscape indices in the form of value functions. There were considerable differences between the value functions of the individual respondents, between the different indices, and between the resulting maps at different scales. In general, fragmentation patterns that were somewhere in between the two extremes were preferred, reflecting the respondents' concerns for the needs of several species. In most cases, the value functions obtained for the small scale functions were more regular in form than those for the large-scale maps. The large-scale maps often exhibited several local maxima and minima within a small range of index values, which suggests that the indices did not always reflect all of the variables considered by the respondents when assessing maps. Moreover, in some cases, the ranking of the maps changed when the index of measurement changed, which supports the assumption that the indices measure different aspects of fragmentation and are not directly correlated with one-another. The evaluations of the different respondents also varied considerably, even though they were all well acquainted with the problem and its dynamics.

In Paper III, the landscape indices assessed in Paper II were used to define objectives relating to the structure of the landscape. In all cases, the index used in the optimization process had a clear and unique effect on the resulting landscape pattern. Moreover, the amount of habitat available in the landscape was related to the differences between the fragmentation patterns for different indices. AvgArea and Nr were found to correlate positively, both in terms of the values of the indices and in terms of the structures of the landscapes obtained by optimizing against objectives targeting these variables. In both cases, solutions were obtained that had relatively large habitat patches consisting of several stands. However, it was more efficient to maximize AvgArea than to minimize Nr because the heuristic algorithm found better solutions in terms of both AvgArea and Nr when using objectives based on AvgArea. The minimization of dNN resulted in a landscape consisting of groups of small stands, especially when using the BAU data set (which yielded a relatively small amount of habitat space). While the resulting solutions had low dNN values, the spatial distribution of habitat sites did not reflect the broader goal of reducing the landscape's fragmentation. Somewhat similar results were obtained when optimizing based on SI: when the overall amount of habitat space within the landscape is small, the optimization algorithm yielded small, regularly shaped stands. It thus appears that minimizing the SI does not necessarily reduce the internal fragmentation of the landscape. On the other hand, when using the BL data set (which was designed to increase the area planted with broadleaved trees and thus the habitat space within the landscape), optimization based on the SI had a very pronounced and positive effect on the fragmentation of the landscape, efficiently combining isolated stands into contiguous patches.

The results presented in Paper IV are consistent with previous research on the development of lichen-rich areas in northern Sweden: under BAU-type forest management, the abundance of pasture areas decreased significantly, and they had almost disappeared by the end of the 100-year planning horizon. The abundance of pasture areas also decreased under the ADJ and NPV scenarios during the first few decades of the planning horizon, primarily because young stands within the studied landscape grew to heights of more than 3 m during this period. However, this decrease stopped as the simulations progressed, and then started to reverse. In the ADJ scenario, the abundance of pasture areas was slightly greater at the end of the 100-year planning horizon than it had been at the start. In economic terms, the ADJ plan reduced the NPV of the forest by 5 % relative to the BAU scenario. Conversely, the NPV scenario increased the NPV of the forests in the northern part of the studied region by 2% and reduced that in the southern part by the same amount relative to the BAU results.

The most important factor in determining the abundance of pasture areas was found to be the use of CCF management. The adoption of this management regime increased the abundance of pasture areas over the planning horizon relative to the BAU scenario, with a particularly pronounced increase occurring during the latter half of the simulation period, especially in the ADJ scenario. In simulations where CCF was not used, the abundance of pasture areas decreased considerably under the ADJ scenario. However, in contrast to the BAU scenario, they did not disappear altogether. This suggests that the loss of pasture areas over the next few decades cannot be prevented by increasing the frequency of pre-commercial thinning alone. However, this approach may prevent pasture areas from disappearing in the long run, even in the absence of other changes such as the introduction of CCF.

# 5 Discussion and conclusions

The individual studies included in this thesis approach the elicitation and application of spatial preferences in forest planning problems from different angles. This section discusses the results of the individual studies in the context of spatial preferences.

Paper I shows that spatial preferences are more difficult to elicit and articulate than preferences dealing solely with amounts of a given objective. Paper II presents a method to tackle this problem, improving the elicitation of spatial preferences on biodiversity values in a forest landscape. Paper III formulates the fragmentation objectives of Paper II into forest plan alternatives, highlights specific issues connected to different fragmentation measures and gives guidance towards a choice of a suitable set of fragmentation measures. Paper IV presents a planning problem where the spatial criteria and objectives were more complicated, as they depend on neighborhood relations and temporal changes. The approach of Paper IV is to develop realistic future scenarios and suggest measures for evaluating these scenarios, both in numerical terms and on maps. This setup could then be used as a basis for discussion between the DMs and stakeholders, possibly using a decision aid such as PlanEval in Paper I.

The MCDA process used in the case study presented in Paper I proved to be useful as a tool for learning and identifying the different trade-offs involved in managing the forests within the studied area. The thorough intelligence-design-choice process also revealed important differences between the DM's stated and revealed preferences, especially with respect to NPV. In a multi-objective forestry setting as that described in Paper I, it can be difficult to compare the perceived strength of the DM's preferences regarding economic profits and other factors using MCDA. The concept of MCDA is based on the assumption that the criteria included in the process are truly comparable (Keeney, 1992). However, the behavior of the DM in this case study raises the question of whether MCDA is a suitable method for comparing timber production objectives in a forest management planning situation to non-timber production objectives, or whether some other approach might be more suitable for the choice phase.

Paper I also features an assessment of the PlanEval software with respect to its usefulness in evaluating different forest plans. It was found to be a helpful tool for the analyst because it provides direct access to the data underpinning each of the suggested forest plans during the evaluation process, and enables the examination of these data in multiple ways. However, several technical obstacles were encountered when evaluating the proposed plans. The most prominent of these had to do with the difficulty of analyzing the maps associated with the different plans. The impact of different plans on some specific places could be analyzed and compared with relative ease, but in general it proved to be difficult to evaluate and compare the maps in a meaningful way. When the maps were studied on a small scale, it became difficult to identify differences between them. However, attempts to analyze the maps on larger scales, to consider multiple scales simultaneously, or to examine alternative representations of the underlying data made the evaluations very time-consuming and cognitively challenging. Similar observations have previously been made by Uran and Janssen (2003), who reviewed several spatial decision support systems (SDSS) and identified various reasons why users might be reluctant to adopt them as decision aids. Some of the problems identified in their study, such as the provision of excessive detail, the time-consuming nature of the evaluations, the need for extensive training, and limitations on the availability of time and resources were also encountered in our study, and should be considered seriously in the future development of the PlanEval system. Belton and Hodgkin (1999) discussed decision support systems (DSS) from the point of view of different end-users, and concluded that expert and non-expert users differ significantly in the features they require from a DSS. Overall, the results presented in Paper I suggest that PlanEval can be regarded as a promising tool for expert users and for use in expert-driven processes.

The findings of Paper I emphasize a need for more structured methods to elicit spatial preferences than pure comparisons of maps. In paper II, value functions were developed to analyze preferences regarding landscape structures in straightforward numerical terms. The SMART technique was used to compare the landscape maps and proved to be simple and easy to understand, and the evaluations were easily performed within the allocated 20 minutes (see Paper II). As was the case in Paper I, the respondents noted that structured approach to preference elicitation used in this work served as a valuable learning process in and of itself. The SMART results revealed that most of the respondents preferred a landscape structure that was somewhere in between the two extremes that were put forward. This is valuable information for the formulation of landscape-level goals in forest planning, showing that the widely used maximum and minimum formulations may not always reflect the real preferences of the DMs correctly.

When applying preference information in forest planning calculations, there is a need for numerical indicators that can be used to quantify the relevant objectives. The spatial indices used in Paper II describe habitat fragmentation in terms of variables such as patch size, shape, amount, and the isolation of patches within the landscape. Respondents were asked to assign scores to each of the variables considered based on their perceived importance and these scores were used to draw up value functions to be used when evaluating the desirability of the landscape distributions shown in different maps. However, the forms of the value functions differed from index to index, and in some cases, the ranking of the maps changed depending on the index. This observation reflects the fact that different indices measure different aspects of fragmentation, and suggests that the use of a single measure of fragmentation could lead to the neglect of characteristics that would be revealed by considering other indices. The findings presented in Paper II thus emphasize the need to choose landscape indices carefully when attempting to formulate plans that will favor the preservation or creation of specific landscape structures.

In Paper III, we used the landscape indices described in paper II to establish objectives that could be used in forest planning. The purpose was to compare the usefulness of the different indices in drawing up landscape objectives for long-term forest planning. To simplify the analysis, we did not use the value functions presented in Paper II, but instead assumed monotonous preferences for each spatial index aimed at either maximizing or minimizing their value. The results obtained were consistent with the observation made in Paper II: the indices used to describe fragmentation do not measure "fragmentation" *per se*, but instead reflect slightly different aspects of fragmentation patterns. That is, the landscape patterns obtained by focusing on specific indices sometimes differ significantly from those obtained by optimizing towards other indices. This study also revealed a striking relationship between the degree of fragmentation within the landscape and the total amount of habitat space. In some cases, high levels of fragmentation were observed when optimizing against a specific index given a small habitat space (i.e. under the BAU conditions). However, optimization against the same index under conditions that allowed for an increase in the overall habitat space (i.e. the BL conditions) yielded large contiguous areas of broadleaved trees. The amount of habitat space had a particularly strong effect on the optimizations based on the dNN and SI indices: with a small total habitat area, minimizing these indices produced small, isolated patches of habitat. However, when large amounts of habitat space were available, optimization based on the SI index efficiently produced large contiguous patches of habitat space. This suggests that it may be useful to use some combination of multiple indices or an index that accounts for both the value of certain indices and the total available habitat space when attempting to establish an ecologically optimal landscape structure.

In more general terms, the simulations presented in Paper III also reflect the importance of defining and structuring preferences correctly and fully. In the case study, we assumed a realistic multi-objective planning problem with two objectives: 1) to maintain stable harvests over the planning horizon, and 2) to minimize habitat fragmentation, maximize NPV, or maximize the total habitat space. The performance of each plan with respect to the non-spatial objectives is easy to evaluate: the greater the corresponding numerical value, the better. However, performance with respect to spatial objectives is more difficult to evaluate. It is not sufficient to simply consider the numerical values of the spatial indices because inspection of the maps reveals details of the solutions that cannot be identified based on numerical data alone. This problem was especially pronounced for the BAU results, for which a constraint or sub-objective regarding the total habitat area would be needed in order to achieve the objective of decreasing the landscape's fragmentation. However, even then the evaluation of the maps would be difficult. For example, how would one determine whether a smaller dNN is more desirable than larger AvgArea? The value functions derived based on the hypothetical data presented to the respondents in Paper II could potentially have been used to evaluate their preferences for one landscape structure over another. Alternatively, the preference information revealed by the value functions could be incorporated into the problem formulation using subutility functions.

The evaluation of the scenarios in Paper IV is also closely connected to the formulation of the preferences. Reindeer husbandry is dependent on the landscape structure as a whole, and so the objectives considered in this work related to the preservation of specific conditions within the forest as well as the spatial and temporal connections between them. To model these objectives, we defined criteria to describe the suitability of the stands for reindeer grazing. These criteria were based on stand and site characteristics, and thus did not have spatial or temporal dimensions in and of themselves. Instead, changes in the spatial distribution of these sites over time were evaluated by considering maps and diagrams that showed the evolution of the study area over time in each simulation. The use of more advanced methods for analyzing the connectivity of the landscape in space and over time would thus have improved the analysis considerably. This could potentially have been achieved by means of landscape pattern modeling as discussed in Papers II and III. Specifically, it may have been possible to establish a landscape index that would describe the connectivity of the pasture areas in the landscape, such as spatial autocorrelation function (e.g. Moran's *I*). By calculating the value of such an index for each planning period separately, one would also be able to analyze changes in the landscape's structure over time. However, there are some problems associated with this approach. First, indices that specifically describe connectivity are hard to find – even the suggested spatial autocorrelation index actually measures the clustering of the landscape rather than connectivity as such. Second, the landscape preferences for reindeer husbandry may actually be better reflected by for example network modeling processes than by static descriptions of the landscape pattern at a given time. Reindeer move over the landscape in herds, grazing on a stand or neighboring stands and then moving on to the next lichen-rich area. Therefore, the nature of the sites within the immediate vicinity of a given pasture area is more interesting than distant pasture sites in terms of modeling the movement of the herd. It is also important to note that the accessibility of specific neighboring sites will depend on the weather conditions and the harvesting of the forest. By the same token, even stands that have relatively little lichen may be important for reindeer husbandry if more lichen-rich stands become inaccessible for whatever reason.

In this thesis, I have investigated and discussed the importance of a careful preference elicitation process. The cases studied in this thesis provide insight into the tradeoffs between different objectives, offer means to make the planning process more efficient, and thrive to ensure that the final choice of plan alternatives matches the decision maker's values as correctly as possible.

# 6 Future work

During the preparation of the papers included in this thesis, extensive consideration was given to how these studies could be progressed and to the identification of fundamental questions to be addressed in the future.

Paper I identified problems in assessing both spatial and temporal data within a DSS. In the future, particular emphasis should be placed on the development of simple, logical user interfaces for DSS programs, and to providing more support for the analysis of maps. The implementation of a spatial preference elicitation method such as that described in Paper II into a DSS would also be of interest. The use of new technology, such as touchpads and smartphones, could also offer new possibilities for interactive evaluations of spatial data, in combination with methods such as that described in Paper II.

Based on the results presented in Paper II, it seems that it would be sensible to combine the value functions based on the responses of different individuals into an aggregate measure of group consensus. Such a measure could then be used to evaluate different scenarios developed using the approach outlined in Paper III, and to form a subutility function that would more accurately reflect the preferences of DMs. Moreover, the impact of map scale on the DMs' stated preferences should be investigated in more detail. For example, should different methods of elicitation be used when working with maps of different scales?

It would be interesting to analyze the landscape indices presented Paper III to determine the effect of varying the total habitat space, and to develop combined indices that account for this factor alongside the other variables considered. Other methods for solving the problem instead of the SA used in Paper III could also be tested.

In Paper IV, strong simplifications and assumptions were made with respect to the prevailing forest management practice, as well as to the effects of the different forestry treatments. Further research on the effects of the treatment models are thus needed to validate the results of Paper IV. Another important factor that was possibly oversimplified in Paper IV is the definitions of primary and secondary pasture, areas with different proportions of lichen in the ground layer that are suitable as reindeer pasture. In particular, the scope for including a spatial dimension in this definition would be an interesting topic for future research. The establishment of such a measure might make it possible to better understand the dynamics of reindeer grazing and thereby identify management regimes that satisfy the requirements of both reindeer husbandry and commercial forestry.

More generally, the issues associated with eliciting preferences regarding changes over time were not addressed in this thesis. However, this is an important challenge, especially in long term forest planning. The tradition of discounting future economic profits to present date is based on the assumptions of preferring near-future events to those farther away in time. As of today, there is no such mechanism for discounting factors other than timber production in forest planning. Therefore, in order to improve the utility of multi-objective planning, techniques for eliciting and describing the changes in preferences over time with respect to non-timber objectives are required.

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I woke up in a tent at the root of Norway's national mountain Stetind after an epic 23-hour-climb, when my phone rang. Ljusk Ola Eriksson called to inform that I had a chance to do a Ph.D. in Umeå. On our way back home, we took a quick glance at the impressive Blåberget in Bjurholm, and the less impressive indoor wall at IKSU, and decided to move to Sweden. Now, after four and a half years, I am certain that this was the right choice to have made.

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Saku. Without you, this thesis could maybe have been finished even sooner… But I would have missed so many other things in life. And I would still be climbing 6b. On top rope.