Development and Evaluation of Forest Management Scenarios

Long-term Analysis at the Landscape level

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Abstract

Managing forests sustainably is an intricate task, as forests are dynamic, complex, and long-lived ecosystems. At the same time, demands on forests are increasing and diversifying. To deal with these challenges, forest decision support systems have been developed that allow one to project the development of forests and the ecosystem services they can provide in the future. This thesis develops and evaluates long-term forest scenarios for two landscapes in Sweden by considering economic, ecological, and social aspects of sustainable forest management. One aspect considered in the scenario analysis is how forest ownership structure influences forest management. When examining factors that influence forest owners' management decisions property size was found to be more influential than other factors such as gender or residence of the forest owner. Based on these results, two methods to account for a diverse forest ownership structure in long-term forest scenarios were developed. It was shown that forest owners' management behaviour can have considerable effects on the provision of ecosystem services, suggesting that accounting for the diversity in forest owners' management behaviour deserves more attention in future projections of the development of forests and the resulting ecosystem services. In addition, this thesis evaluated different management options based on expert participation in a multi-criteria decision analysis framework. Results indicate that several management scenarios would be better suited to balance multiple forest values than a continuation of current practices. Finally, this thesis tests a method that assesses the trade-off between wood production and recreational values to identify areas where adapted management should be prioritized. The results show that substantial increases in the recreational value of a forest landscape can be achieved with a moderate overall reduction of timber production revenues. In conclusion, the papers included in this thesis clearly demonstrate that long-term landscape level scenarios can be useful tools for illustrating trade-offs between different ecosystem services, for evaluating different management practices, and for assessing potential future developments, providing valuable input for forest governance and decision making at different levels.

Keywords: ecosystem services, landscape, long-term planning, forest decision support system, forest owner behaviour, management strategies, scenario analysis, trade-offs

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Utveckling och utvärdering av långsiktiga skogliga skötsel-scenarier på landskapsnivå

Det huvudsakliga syftet med skogsbruket i Sverige har traditionellt varit virkesproduktion med en hög ekonomisk avkastning. Under de senaste decennierna har dock andra målsättningar och krav uppmärksammats allt mer och skogsbruket försöker därför i högre grad balansera ekonomiska, ekologiska och socio-kulturella värden. Skogen förväntas exempelvis spela en viktig roll i övergången till en biobaserad ekonomi, bidra till begränsningen av klimatförändringar, vara en attraktiv rekreationsmiljö för en ökande urban befolkning, samtidigt som man vill bevara artmångfalden och viktiga livsmiljöer för hotade arter. Om skog ska brukas på ett hållbart sätt med hänsyn till dessa olika värden behövs kunskap om hur skogsskötseln påverkar de olika värdena. Därmed kan skogsskötseln styras så att en önskvärd balans erhålls mellan de olika värdena. Detta är dock komplicerat, eftersom skogen är ett dynamiskt och komplext ekosystem, som behöver betraktas över långa tidshorisonter. Det är bland annat för att hantera dessa utmaningar som skogliga beslutsstödsystem utvecklats. Systemen beskriver skogens utveckling och de ekosystemtjänster som skogen tillhandahåller. Det görs ofta i form av scenarier, det vill säga en framskrivning av skogens tillstånd givet vissa förutsättningar och antaganden. Ofta jämförs ett antal olika scenarier med olika antaganden för att få en uppfattning om vilka konsekvenser dessa ger upphov till, som till exempel olika inriktningar av skogsskötseln. Scenarier på landskapsnivå är särskilt användbara vid bedömningar som omfattar flera ekosystemtjänster eftersom man kan inkludera den lokala mångfalden av beståndstyper, trädslag och åldersfördelningen samt ägarförhållanden.

Denna avhandling utvecklar och utvärderar skogliga scenarier på landskapsnivå genom att beakta hur olika skötselscenarier påverkar ekonomiska, ekologiska och socio-kulturella skogliga värden. Avhandlingen beaktar skogsägarna som en heterogen grupp med olika intressen och preferenser och integrerar olika ageranden i analyserna, vilket sällan gjorts i tidigare studier. Empiriskt utgår avhandlingen från två olika svenska kommuner. Tre av de ingående studierna fokuserar på skogsägare och deras val av skötselstrategi, samt hur ägarstrukturen kan avbildas i skogliga scenarier. En analys av faktorer som påverkar skogsägare i deras val av skötselstrategi visar att skillnader mellan olika kategorier av ägare, till exempel kvinnliga och manliga ägare och ägare som bor nära eller långt ifrån fastigheten, är ganska liten. Däremot har storleken på skogsfastigheten betydligt större inverkan på ägarens val av skötselstrategi. Dessa resultat beaktades i de följande två studierna där olika scenarier utvecklades och jämfördes med hjälp av det skogliga beslutsstödsystemet Heureka. Scenarioanalyserna innehåller två metoder för att ta hänsyn till ägarstrukturen i skogslandskapet. I båda metoderna länkas olika kategorier av skogsägare till olika skötselstrategier. I den ena studien analyserades effekterna av skillnader i skogsägarnas agerande på ekosystemtjänster kopplade till ekonomiska, ekologiska och socio-kulturella skogliga värden, medan den andra studien utvecklade tre olika framtidsscenarier som påverkades

av skogsägarnas agerande gällande skogsskötseln. Studierna visar att skogsägarnas agerande kan ha tydliga konsekvenser för utfallet av ekosystemtjänster - och därmed ekonomiska, ekologiska och socio-kulturella skogliga värden - på landskapsnivå redan efter 20 år. Det tyder på att hänsyn till skillnader i skogsägarnas agerande förtjänar mer uppmärksamhet i framtida scenarieanalyser.

I avhandlingen ingår även deltagande av experter för att utvärdera olika alternativa skötselinriktningar. För detta användes Heurekas programvara för flermålsanalys, PlanEval. Resultaten indikerar att flera alternativa scenarier till det scenario som implementerar en fortsättning av dagens skogsbruk, vilket lägger relativt stor vikt vid ekonomiska värden, är bättre lämpade för att balansera skogens olika värden. Slutligen testas en metod för att göra avvägningar mellan virkesproduktion och rekreationsvärden genom att identifiera områden där anpassad skogsskötsel bör prioriteras. Här används ett rekreationsindex sammansatt av dels ett beståndsindex, som beskriver hur lämpligt ett bestånd är för rekreation, dels ett lägesindex vilket beskriver skogens tillgänglighet främst baserat på befolkningstätheten inom gångavstånd. Genom att definiera olika skötselalternativ och variera nivån av hänsyn till rekreation i optimeringsverktyget i Heurekas programvara PlanVis fördelas skötselalternativen på bästa sätt. I den fallstudie som genomfördes kunde rekreationsvärden gynnas genom att fördela olika skötselstrategier strategiskt inom landskapet med måttlig inverkan på virkesproduktionens ekonomi.

Sammanfattningsvis visar resultaten från studierna att långsiktiga skogliga scenarier på landskapsnivå är användbara verktyg för skogsförvaltning och beslutsfattare och betonar vikten på att ta hänsyn till ägarstrukturen och dess inverkan på skogsskötseln. Scenarierna kan användas för att utvärdera olika skötselinriktningar, bedöma möjliga utvecklingsvägar och för att göra avvägningar mellan olika ekosystemtjänster.

Failing to plan is planning to fail.

Benjamin Franklin

Contents

List of Publications

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

I Eggers, J., Lämås, T., Lind, T., Öhman, K. (2014). Factors influencing the choice of management strategy among small-scale private forest owners in Sweden. *Forests* 5(7), 1695-1716.

II Eggers, J., Holmström, H., Lämås, T., Lind, T., Öhman, K. (2015). Accounting for a diverse forest ownership structure in projections of forest sustainability indicators. *Forests* 6(11), 4001-4033.

III Eriksson, L. O., Nordström, E.-M., Eggers, J., Sandström, S., Carlsson, J. Modelling ecosystem services and forest owner behaviour through scenario analysis on a landscape level. (submitted manuscript)

IV Eggers, J., Holmgren, S., Nordström, E.-M., Lämås, T., Lind, T., Öhman, K. Balancing different forest values: Evaluation of forest management scenarios in a Multi-Criteria Decision Analysis framework. (submitted manuscript)

V Eggers, J., Lindhagen, A., Lind, T., Lämås, T., Öhman, K. Balancing landscape-level forest management between recreation and wood production (manuscript).

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The contribution of Jeannette Eggers to the papers included in this thesis was as follows:

I Conducted the research design and analysis, writing and review process with counselling from supervisors.

II Designed the study in cooperation with the co-authors, performed the analysis and wrote the major part of the manuscript.

III Contributed to the design of the study and wrote a minor part of the manuscript.

IV Designed the study in close cooperation with the co-authors. Performed the analysis and wrote the major part of the manuscript, all in discussion with the co-authors.

V Planned the study in cooperation with the co-authors, performed the analysis, and wrote the major part of the manuscript.

Abbreviations

AHP	Analytic Hierarchy Process
CCF	Continuous Cover Forestry
DSS	Decision Support System
FSC	Forest Stewardship Council
LP	Linear Programming
MCDA	Multi Criteria Decision Analysis
MILP	Mixed-Integer Linear Programming
NFI	National Forest Inventory
NIPF	Non-Industrial Private Forest
NPV	Net Present Value
SFM	Sustainable Forest Management
SMART	Simple Multi-Attribute Rating Technique

1 Introduction

1.1 Background

Traditionally, the main objective of forest management was to increase wood production and economic returns. However, the need to consider other goals in addition to wood production has increasingly been recognized in recent decades, and the focus of forestry has shifted from sustained yield management to sustainable forest management (SFM) (Hahn and Knoke 2010), which is now the globally prevailing forest management paradigm (MacDicken *et al.* 2015). The starting point of SFM, which aims to balance economic, ecological, and socio-cultural forest functions, is connected with the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro and the adoption of the "Forest Principles" (Siry *et al.* 2005, Hahn and Knoke 2010). There exists no globally agreed definition of SFM. On the European level, SFM is defined as "The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems." (MCPFE 1993). On global level, the importance of forests and their sustainable management was recently emphasized in the United Nation's Sustainability Development Goals of the 2030 Agenda for Sustainable Development, in particular in goal 15 that aims to "protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation and halt biodiversity loss" (UN 2017).

The increasingly popular framework of ecosystem services acknowledges the dependency of human well-being on receiving multiple benefits from the environment and has much in common with the SFM concept (Quine *et al.* 2013). Ecosystem services, defined as "the benefits people obtain from ecosystems" (MEA 2005), are increasingly mapped, valued, and marketed (Burkhard *et al.* 2012, Schomers and Matzdorf 2013, Costanza *et al.* 2014, Hansen and Malmaeus 2016, Englund *et al.* 2017). The need to manage and balance multiple ecosystem services across landscapes is increasingly emphasised (Nelson *et al.* 2009, de Groot *et al.* 2010, Raudsepp-Hearne *et al.* 2010, Triviño *et al.* 2015), and the importance of landscape protection, management, and planning is highlighted politically through the European Landscape Convention (Council of Europe 2000). Forest landscapes provide a multitude of ecosystem services, including the production of wood and non-wood products, carbon sequestration, recreation, and watershed protection. Therefore, maintaining forest ecosystem services can be considered to go hand-in-hand with SFM, and the valuation and marketing of ecosystem services has the potential to enhance SFM (Deal *et al.* 2012). However, managing forests sustainably for the provision of multiple ecosystem services is an intricate task as forests are dynamic, long-lived, and complex systems. Most forest ecosystem services are sensitive to forest management to some extent, and trade-offs as well as synergies between wood production and other important ecosystem services have been identified (Duncker *et al.* 2012, Biber *et al.* 2015). Additionally, the consideration of multiple forest ecosystem services across landscapes often calls for the involvement of multiple stakeholders (Nordström 2010), and climate change adds uncertainties regarding future growing conditions and disturbance regimes (Lindner *et al.* 2014). Another factor that has bearing on forest management and planning is forest ownership structure, as management objectives and behaviour often vary between different owners. Finally, as forests grow slowly, forest management and planning need to deal with long time horizons, and it takes time before changes in management can influence ecosystem services on the landscape and on larger scales. As a result, computer models are frequently used to project the impact of, for example, changes in management on the development of ecosystem services over time. Often several different scenarios (i.e., alternative futures based on different pathways of choices) are compared, so that the consequences of different sets of actions on future forest development and the provision of ecosystem services can be analysed and compared. Knowledge of the potential development of forest ecosystem services is of key importance for forest planning and governance. Analysing and evaluating the potential development of forest ecosystem services is the focus of this thesis. Specifically, in this thesis long-term landscape-level forest management scenarios are developed, addressing factors such as ownership structure, the increased interest in more varied management, and the conflict between wood production and outdoor recreation. The scenario results are evaluated in terms of how they balance different forest values.

The following section provides an overview of the theoretical framework of this thesis by describing the tools used in forest planning to support decision making. Next, a brief discussion is provided that addresses how and to what extent forest owner behaviour is accounted for in projections of forest ecosystem services. Then, some background on forest management and planning in Sweden is given, before turning to the specific objectives of this thesis. Finally, the papers included in this thesis are summarized and discussed.

1.2 Decision Support Systems

The increasing complexity in forest management and planning, aided by rapid developments in computing systems, has spurred the development of computer-based forest decision support systems (DSS), i.e. "computer-based systems that help decision makers to analyse and solve ill-structured decision problems by integrating database management systems with analytical and operational research models, graphic and tabular reporting capabilities, and the expert knowledge of scientists, managers, and decision makers" (Vacik *et al.* 2015). DSS typically include three fundamental components: a modelling subsystem, a database management subsystem, and a user interface (Watson and Sprague 1993, Power 2002, Vacik *et al.* 2015). Various sets of criteria and indicators are used to assess the development of ecosystem services and SFM in projections of forest ecosystem services. Which indicators can be used in these projections naturally depend on the forest DSS used. While early DSS were designed to address relatively narrow, well-defined problems, more recent systems tend to be used for more general purposes and are multifunctional, allowing for the assessment of multiple forest ecosystem services (Reynolds *et al.* 2008). Modern DSS can therefore be used for diverse decision-making problems at different temporal and spatial scales (Nobre *et al.* 2016). Thus, many modern DSS can be used not only for the planning and timing of management activities but also for assessing the impact of different management practices on the provision of a multitude of ecosystem services.

Three temporal levels are usually distinguished for planning problems in forestry in a hierarchical system: long-term (strategic), covering a time-span of at least ten years, but often covering a whole rotation period; medium-term (tactical), covering a time span of two to ten years; and short-term (operational), covering a time span typically covering one month or less (Bettinger *et al.* 2009, Eriksson and Borges 2014). *Strategic planning* focuses on the long-term achievement of management goals. Large forest owners use strategic planning to estimate the allowable cut and for strategic decisions on, e.g., regeneration measures. At this stage, a DSS can assist in, for example, choosing optimal forest management for maximum net present value or timber harvest while also considering ecological and social forest values. Strategic planning is also used for projecting and evaluating the consequences of different management strategies on the long-term provision of ecosystem services (Biber *et al.* 2015, Frank *et al.* 2015), for analysing trade-offs between different ecosystem services (Garcia-Gonzalo *et al.* 2014, Nordström *et al.* 2015, Triviño *et al.* 2017), for reserve selection (Lundström *et al.* 2011), and for including the preferences of various stakeholders in the planning process (Nordström *et al.* 2013, Aldea *et al.* 2014, Nilsson *et al.* 2016). *Tactical planning,* on the other hand, is concerned with assigning management measures, such as harvesting and thinning, to forest stands, resulting in an inventory of stands that are available for harvest or thinning within five to ten years. Large forest owners often use a DSS to help allocate stands for harvest such that costs for road construction or upgrading and moving harvesting teams are kept low. Finally, *operational planning* is concerned with scheduling and implementing the actual forest operations on a day-to-day, monthly, or annual basis. DSS can be used, for example, to minimize costs, to determine optimal routes for transport, or to minimize the degradation of habitats or other ecological values (Bettinger *et al.* 2009).

Forest DSS can be designed to solve problems on different spatial scales, such as the stand level, forest or landscape level, and regional or national level. Examples for stand-level systems include MOTTI (Hynynen *et al.* 2005, Triviño *et al.* 2017), SILVA (Pretzsch *et al.* 2002), 4C (Reyer *et al.* 2014), Heureka StandWise (Wikström *et al.* 2011, Subramanian *et al.* 2015), and CARBWARE (Black 2016). DSS designed to work on forest or landscape level, including Heureka PlanWise (Wikström *et al.* 2011) and MELA (Nuutinen *et al.* 2011), often make use of optimization techniques. DSS applied at regional or national scales include Heureka RegWise (Claesson *et al.* 2015) and EFISCEN (Schelhaas *et al.* 2007). However, many forest DSS can be used to work at different spatial scales.

Forest DSS make use of many modelling approaches. The models describing forest dynamics can be empirical (the typical approach for growth and yield models in forestry), mechanistic (process models), or forest succession models (Peng 2000, Larocque 2016). Empirical models are usually based on data from forest inventories or long-term forest experiments (Burkhart and Tomé 2014) and are less data-demanding compared to process models; however, empirical models are less reliable in the context of environmental changes (Fontes *et al.* 2010). Process models, on the other hand, simulate the underlying processes that are thought to influence, for example, tree growth and mortality, so they are more data intensive (e.g., high-resolution data input and short time steps). Empirical models are more suitable for assessing the effect of changes in management, whereas process-based models are more suitable for assessing changes in environmental conditions, given that enough data exist to calibrate the models. Empirical and process models can also be coupled, for example, by using the simulated changes in productivity caused by environmental changes from a process model to scale forest growth in an empirical model (e.g., Eggers *et al.* 2008). Successional models depict successional pathways for seedling establishment, tree growth, and mortality and can include process-based as well as empirical components (Larocque 2016). Such models may be preferable when ecological aspects are the questions at issue.

Different problem-solving methods are used in forest DSS, and one way of classifying DSS methodologically is to distinguish between three different groups: DSS based on simulation, DSS based on optimisation, and DSS used for multi-criteria decision analysis (MCDA) (Nobre *et al.* 2016). The following sections give a short summary of these three methodological groups, with a focus on long-term forest planning problems.

1.2.1 Simulation

Irrespective of the modelling method, simulation in the context of a forest DSS means that forest management rules are specified, and the outcome is based on an application of these rules (Nobre *et al.* 2016). The simulator thus projects the likely development of the forest, and the resulting ecosystem services under pre-defined management rules. Simulators are useful for answering "what if" questions, i.e., for assessing the consequences of certain actions. Simulation is a frequently applied technique at all spatial scales (Nobre *et al.* 2016). Examples of forest DSS that apply simulation include the RegWise module of the Swedish Heureka system (Wikström *et al.* 2011), the European Forest Information Scenario Model EFISCEN (Schelhaas *et al.* 2007), and the landscape simulator LANDIS-II (Scheller *et al.* 2007).

1.2.2 Optimisation

DSS based on optimization methods, on the other hand, generate a set of alternatives from which the best alternative is selected using an optimising algorithm based on the goals and constraints of the planning problem. These kinds of DSS can be used for answering "How to" questions, i.e., for finding the optimal way to reach certain objectives. Optimisation problems thus require that the user defines forest management goals and constraints rather than strict management rules. Therefore, optimisation techniques are often applied on the property level although stand- and regional-level applications are also common (Nobre *et al.* 2016). Several mathematical models for optimizing stand-level management regimes have been developed during the last 60 years, including linear, non-linear, and dynamic programming as well as heuristic methods (Bettinger *et al.* 2009). Linear programming (LP) is widely used in long-term forest planning, often for finding optimal management schedules (Bettinger *et al.* 2009). For this purpose, many treatment schedules are produced for each treatment unit (typically a forest stand). The LP model includes an objective function that specifies which variable should be maximized or minimized and one or more constraints that set limitations on the planning problem. A basic assumption in LP is that all relationships in the model are linear and that all decision variables are continuous real numbers. This allows for treatment units to be divided to receive different treatment schedules. In mixed-integer linear programming (MILP), this assumption is relaxed, allowing some of the decision variables to be integers. MILP is useful if treatments should always cover whole stands rather than parts of stands as in LP.

Examples of forest DSS that apply optimization include the PlanWise module of the Swedish Heureka system (Wikström *et al.* 2011), the MELA system, which has been in use in Finland since the 1980s (Nuutinen *et al.* 2011), and the ArcGIS extension Optimal developed for Czech forests (Marušák *et al.* 2015).

1.2.3 MCDA

The third methodological group is forest DSS used for MCDA. MCDA is the collective term for mathematical methods used to find solutions to decision problems with multiple conflicting objectives, given the decision maker's preferences. MCDA is a widely-used approach for solving complex resource management problems, including forest management and planning (Kangas and Kangas 2005, Mendoza and Martins 2006, Diaz-Balteiro and Romero 2008, Ananda and Herath 2009). Although originally developed for a single decision maker, MCDA processes allow for the participation of stakeholders and for group decision making (Nordström 2010). MCDA supports decision makers and stakeholders in making trade-offs between objectives through a structured process that aims to identify solutions that fit the objectives in the best possible way. MCDA methods allow for the comparison of values measured by different scales without the need to convert all criteria to a common scale. There exists a large number of different MCDA approaches, including goal, aspiration, or reference level techniques, outranking techniques, and value measurement techniques (Belton and Stewart 2002, Mendoza and Martins 2006). Value measurement techniques are frequently used in forest and other natural resource management (Mendoza and Martins 2006). This technique was used in this thesis and is therefore described in more detail. Value measurement techniques require first generating a set of plans either by simulation or optimization upon which the plans are evaluated based on multiple criteria. An MCDA process using a value measurement technique usually consists of four steps:

- i) The process usually starts with identifying the objectives and arranging them in a hierarchical structure. In the case of participatory forest planning, all relevant stakeholders should be included in this step (Nordström 2010).
- ii) Alternatives are identified or created such as alternative forest plans or scenarios. For assessing the possible impact of each alternative,

one or more attributes are used to measure how well the different alternatives perform in terms of a certain objective.

iii) Preference values are elicited from the decision-maker(s) by weighing the objectives and attributes according to their relative importance.

iv) Finally, the alternatives are evaluated and compared. This step often includes a sensitivity analysis of the results.

Value measurement techniques involve that numerical preference scores are established, representing the degree to which one alternative may be preferred to another (Belton and Stewart 2002). To establish preference scores, attributes and objectives are weighed, for example, using the Simple Multi-Attribute Rating Technique (SMART) (Winterfeldt and Edwards 1986) or using pairwise comparisons such as the Analytic Hierarchy Process (AHP) (Saaty 1990). An alternative for weighing the performance of each alternative in terms of the attributes is to use value functions. Value functions translate the performances of each evaluated attribute into a value score between 0 and 1, representing the degree to which the potential indicator outcome matches the decision objective (Beinat 1997). The advantage of using value functions is that it allows for the evaluation of many alternatives, whereas the number of alternatives that can be compared directly is usually limited to between three and five. As the identification and evaluation of the objectives and attributes often requires case-specific expertise, expert knowledge is frequently used in multi-criteria decision-making (Kangas and Leskinen 2005). Several studies have asked experts to create value functions in an MCDA framework. For example, Store and Kangas (2001) employed stepwise linear value functions to describe habitat suitability. Ananda and Herath (2003) used value functions in regional forest planning to compare three scenarios. Korosuo *et al.* (2013) used value functions to elicit spatial preferences by letting forestry professionals evaluate the spatial distribution of broadleaves in the landscape.

Examples of forest DSS that offer MCDA techniques include the PlanEval module of the Swedish Heureka system (Korosuo *et al.* 2011), the Sim4Tree toolbox (Dalemans *et al.* 2015) used in Belgium, and the SADfLOR system recently developed in Portugal (Garcia-Gonzalo *et al.* 2014)

1.3 Scenario analysis

DSS are frequently used to develop, compare, and evaluate scenarios. In this context, scenarios are defined as "plausible and often simplified descriptions of how the future may unfold based on a coherent and internally consistent set of assumptions about key driving forces, their relationships, and their implications for ecosystems" (Henrichs *et al.* 2010, p. 152). One important aspect of scenarios is that they are not predictions or forecasts, but rather explore the consequences of assumed actions. The main strength of scenario analysis thus lies in comparing different scenarios rather than using one specific scenario as a roadmap for future action (Hengeveld *et al.* 2014). Scenarios can be qualitative (e.g., in the form of storylines), quantitative, or hybrids of these two types (Henrichs *et al.* 2010), combining storylines with quantitative assessments, (e.g. Schröter *et al.* 2005). Forest management DSS deal with quantitative scenarios, projecting the development of the forest into the future using information on today's forest state, ecosystem functions, and assumptions on forest management. Both simulation and optimization approaches can be used for scenario analysis. For example, Shanin *et al.* (2016) used a simulation model to assess ecosystem responses to alternative forest management regimes, while Korosuo *et al.* (2014) used an optimization approach to compare the impact of different management scenarios on forestry and reindeer husbandry. In the case of multiple objective, scenario analysis can be combined with MCDA techniques to support the decision maker in comparing and evaluating the developed scenarios. Such an approach was used, for example, by Nordström *et al.* (2013) to evaluate whether increasing the share of the forest managed with continuous cover forestry is a suitable strategy for a municipality in Sweden.

Scenario analysis can help assess the consequences of various drivers of change, including environmental changes such as climate and land use change, policy changes, or changes in forest management. Scenario analysis in forestry has been conducted on different spatial and temporal scales and is increasingly considering multiple ecosystem services. For example, on the continental level, the impact of climate, land-use, management, and policy changes have been assessed (Nabuurs *et al.* 2006, Eggers *et al.* 2008, 2009, Verkerk *et al.* 2011, Hanewinkel *et al.* 2013, Verkerk *et al.* 2014). On the national level, long-term forestry scenarios can be used to study the potential supply of timber, the consequences of different management scenarios on environmental variables, and the effects of climate change (Claesson *et al.* 2015) to support policy development. Landscape level scenarios allow for a detailed analysis of multi-objective management such that synergies and trade-offs between different objectives can be analysed (Bennett *et al.* 2009, Biber *et al.* 2015, Pang *et al.* 2017). On the forest property level, scenario analysis in combination with multi-criteria decision analysis can help the forest owner(s) find the preferred forest management plan (Eyvindson, Kangas, *et al.* 2010, Eyvindson, Kurttila, *et al.* 2010). At the stand level, scenarios can be used to assess the effect of forest management and environmental changes on specific stands, for example, for developing adaptive management strategies (Subramanian *et al.* 2015).

1.3.1 Accounting for forest owner behaviour

Depending on the research question, the spatial scale, and the temporal scale, as well as the model used to develop the scenarios, different factors are included in the scenarios. Frequently assessed factors include climate change and changes in management. Ownership structure, however, is not regularly included, and its impact of forest management and related development of ecosystem services has not been thoroughly studied (Schaich and Plieninger 2013, Rinaldi *et al.* 2015).

Forest-related values, management objectives, management behaviour, and decision-making styles have been shown to vary among forest owners in a multitude of studies (e.g. Lidestav and Ekström 2000, Boon *et al.* 2004, Ingemarson *et al.* 2006, Dhubháin *et al.* 2007, Nordlund and Westin 2010, Hujala *et al.* 2012, Richnau *et al.* 2013, Hengeveld *et al.* 2014). Therefore, it is conceivable that ignoring the difference in management behaviour among different forest owners and owner types may lead to over- or under-estimations of future ecosystem service provision in projections at the landscape scale or larger scales. Few studies explicitly incorporated different management strategies for different owner categories in long-term assessments. Among the few exceptions is Johnson *et al.* (2007), who applied different management strategies for different owner categories in modelling forest structure, timber production, and socio-economic effects in a multi-owner province in the USA. Johnson *et al.* found that forest structure diverged increasingly over time between the different ownership types. Similarly, Hengeveld *et al.* (2014) accounted for ownership structure in a scenario analysis for a forest landscape in the Netherlands by reflecting the different objectives of the forest owners when simulating their response to climate change, resulting in variations in forest management. Rinaldi *et al.* (2015) propose a framework that links a behavioural harvesting decision model to a forest resource dynamics model, which accounts for different forest owner types in large-scale and long-term analyses. For parametrising the suggested framework, information is needed for each modelled owner type on risk aversion and the preference regarding the timing of monetary revenues from timber sales. The approaches used by Hengeveld *et al.* (2014) and Rinaldi *et al.* (2015) require information on the management objectives of the different owner types and on the distribution of forest area among the different owner types. A similar approach is also applied in this thesis in Paper III. A different approach, used in national forest resource assessments regularly undertaken in Sweden (Gustafsson and Hägg 2004, SLU and Skogsstyrelsen 2008, Claesson *et al.* 2015), is to use logistic regression functions to simulate the probability of future management activities based on observed management from National Inventory Plots (Holm and Lundström 2000). This approach presupposes that historic management behaviour continues in the future and can be applied under different harvesting intensities. Another option would be to use information on management strategies of different forest owner types; this option is tested in Paper II.

1.4 Forest management and planning in Sweden

1.4.1 Forests and forest management

Sweden is a country with rich forest resources: the total forest area is 28.1 million ha of which 23.2 million ha is productive forest, i.e., forest with an average productivity of at least 1 $m^3 ha^{-1} yr^{-1}$ (Skogsstyrelsen 2014a). Most of the forest falls in the boreal zone but some are temperate forest in the southernmost part of the country (Esseen *et al.* 1997). The main tree species in the boreal zone are Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and birch (*Betula sp.*). Long-lived deciduous tree species, mainly European beech (*Fagus sylvatica*) and Pedunculate oak (*Quercus robur*) are present in the temperate zone. Of the productive forest area, 8.4% is exempted from forestry: 3.6% through formal protection (e.g., nature reserves and national parks) and 4.8% through voluntary (non-formal) set-asides for conservation purposes (Skogsstyrelsen 2014a).

In Sweden, about half of the productive forest area is in the hands of private individual owners (also called small-scale, family, or non-industrial private forest (NIPF) owners), with an average property size of 48 ha (Haugen *et al.* 2016). The number of properties owned by the 330 000 NIPF owners is 230 000, which means that a significant share of the private forest properties has several owners. Private-sector companies own 25% of the productive forest area, and the remaining area belongs to the state and state-owned companies (17%), other public owners (2%), and other private owners (6%) (Skogsstyrelsen 2014a). Ownership structure differs along a north-south axis in the country: in southern Sweden, most of the forest (>80%) is owned by NIPF owners, whereas in northern Sweden, various large forest enterprises (both private and public) own a considerable share of the forest area. The share of NIPF owners is smaller in the north than in the south. The characteristics of NIPF owners has changed over the last decades, with an increasing share of female and non-resident owners and a decreasing economic dependency on forests (Haugen *et al.* 2016).

Historically, forests were of utmost importance for the Swedish economy, and the forest sector still makes up 11% of the Swedish export value, and 2.2%

of the gross domestic product (Skogsstyrelsen 2014a, Haugen *et al.* 2016). Forest management had a strong focus on wood production during most of the 20th century. However, nature conservation concerns led to a revision of the Swedish Forestry Act, and in 1994, nature conservation and wood production were given equal importance (Regeringen 1992, Lämås and Fries 1995). The first paragraph of the Forestry Act now reads:

> The forest is a national asset and a renewable resource that shall be managed in such a way that that it provides a sustainable good yield while maintaining biological diversity. Forest management shall also take other public interests into consideration. (SFS 1979) (author translation)

The new Forestry Act gave forest owners considerable freedom in their management decisions after decades of strict regulation (Lidskog and Löfmarck 2016). Few quantitative thresholds for silvicultural or environmental targets are available. Exceptions include the duty to regenerate after a final felling, lowest allowable final felling ages, limitations on clear-cut size in sub-montane forest areas, and prescriptions about the minimum volume to be left on a site after a thinning (SFS 1979).

The governance system is characterized as "freedom under responsibility", largely relying on informational instruments, such as advice and recommendation (Lindahl *et al.* in press, Lidskog and Löfmarck 2016). As the law only stipulates minimum requirements, it is assumed that forest owners can be persuaded to exceed legal requirements for nature consideration in order to reach the objectives set in the forest policy (sectorial responsibility) (Lidskog and Löfmarck 2016).

In the northern half of Sweden, the indigenous Sámi population has the usufructuary right to use the boreal forests as grazing ground for reindeer. Reindeer husbandry is the cultural keystone of the identity and tradition of the Sámi, and reindeer husbandry requires large land areas and availability of forest with good forage conditions (SSR 2009). During the winter, reindeer forage mainly on ground lichen, but in difficult snow conditions, arboreal lichen are important as emergency forage (Horstkotte *et al.* 2015). The Swedish Forestry Act demands that forestry takes reindeer husbandry into consideration and constrains forest management in areas that are used for reindeer husbandry year-round (SFS 1979). However, in most places, the forest is only used as winter grazing grounds, and modern forest management has greatly decreased lichen-rich forest types (Horstkotte *et al.* 2015), a trend that is projected to continue if current forest management practices prevail (Korosuo *et al.* 2014).

About half of the productive forest area (more than 12 million ha) is certified according to the standards of the Forest Stewardship Council (FSC) (FSC Sweden 2017), and almost as much by the Programme for the Endorsement of Forest Certification Schemes (PEFC) (PEFC 2017). More than half of the certified forest area is certified by both FSC and PEFC (Wallin 2017). Both certification schemes request and specify more environmental considerations compared to the Forestry Act. For example, at least 5% of the productive forest area of a certified forest property is to be set aside for nature conservation, and a minimum of ten retention trees per ha are to be left on felling sites. Compared to the Forestry Act, the FSC standard even requires more consideration for the rights of the indigenous Sámi people, requiring consultation for forestry measures planned on all land affected by reindeer herding (FSC Sweden 2010).

In recent years, social forest values, such as recreation and tourism, have gained increasing attention (Sténs *et al.* 2016) in addition to the ecological and economical values of the forest. The importance of recreational forests has been acknowledged by giving local governments the possibility to protect forests that have a high value for recreation through voluntary agreements with land owners (Skogsstyrelsen 2014b).

Despite the increased interest for ecological and social values, Swedish forests are still intensively used for timber production, and both increment and harvest volume have increased over time (*Figure 1*). Forest management is predominantly even-aged with a focus on the two main coniferous species, Norway spruce and Scots pine, usually managed in monoculture. At the stand level, forest management tries to integrate different ecosystem functions by retaining important elements, such as tree groups and buffer zones, during harvest (Gustafsson *et al.* 2012, Simonsson *et al.* 2015). Although there is an increasing interest in alternative management systems, (e.g., continuous cover forestry), the area managed with such alternative systems is small; 2 - 8% of the productive forest area is estimated to be managed with CCF (Cedergren 2008). However, there is now a growing interest in greater diversification of forest management practices. This interest is a response to the increasing pressure and challenges that forestry in Sweden is faced with. More varied forest management is expected to better sustain social, ecological, and economic forest functions in times of growing wood demand and increased risks and uncertainties connected to climate change (Sandström and Sténs 2015, Bergquist *et al.* 2016, Felton *et al.* 2016, Rist *et al.* 2016).

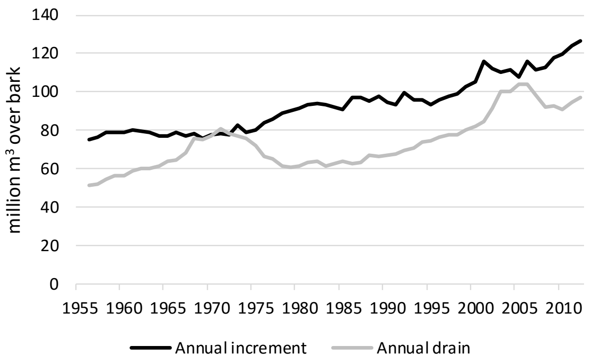


Figure 1. Increment and drain on productive forest area (SLU 2012).

1.4.2 Forest planning

Forest planning is usually done on the property level, and the planning instruments used differ between large forest-owning companies and small-scale owners. Swedish forest owning companies use a typical hierarchical planning structure, with long-term (strategic), middle-term (tactic), and short-term (operational) plans, and use computerized tools such as tailor-made GIS systems, individual tree growth and yield models, and optimization (Nilsson 2013, Lämås *et al.* 2014). The traditionally widely-used tool for long-term forest planning, used by most forest owning companies, the Forest Management Planning Package (Jonsson *et al.* 1993), is now being replaced by the Heureka system, which was developed at SLU and first released in 2009 (Wikström *et al.* 2011). The long-term planning phase includes the implementation of ecological targets through ecological landscape planning (ELP), which aims to balance timber production with the maintenance of biodiversity at landscape level. In this context, landscape is limited to the ownership boundaries as the planning does not include forest properties owned by others.

Forest management plans constitute the most common form of forest planning for NIPF owners. Forest management plans usually contain stand-level descriptions of the forest property, with general recommendations on how to manage each individual stand, for a ten-year period. The plans generally focus on timber production, but nowadays they often contain recommendations for preserving ecological forest values, while social values are rarely considered explicitly (Nordström, 2010). Forest management plans are voluntary except for certified forest properties larger than 20 ha, properties that are required to have a so-called green forest management plan (Brukas and Sallnäs 2012). A green forest management plan resembles a standard forest management plan with the addition that long-term management goals must be specified for all concerned forest stands. These management goals range from setting aside a stand for nature conservation to wood production focus with a certain basic level of consideration for nature conservation. Most forest management plans are prepared by planners at the Swedish Forest Agency or forest owner associations, and owners' objectives are included to varying degrees (Brukas and Sallnäs 2012).

For historical reasons, many municipalities in Sweden own some forest, often located in or near urban areas (Lidestav 1994, Lundquist 2005). Most municipalities have a forest management plan of the same kind as NIPF owners, and their main management goal is often timber production, followed by recreation (Lundquist 2005). Although the importance of recreation is recognized, as many as half of the municipalities lack a clear policy with distinct objectives for their urban forests (Naturskyddsföreningen 2014).

In summary, a common feature for the main planning instruments in use is their focus on timber production, although ecological and to some extent social considerations are increasingly included in the planning process. Forest management plans are the most important planning tool for a large share of the productive forest area in Sweden. Landscape-level planning activities are restricted to forest owners with large and concentrated properties (i.e., companies and the state), and planning spanning several forest properties is rare (Wallin 2017). Forest management plans are usually not communicated between owners (Angelstam *et al.* 2015), so possibilities to consider landscape-level factors are currently limited. However, landscape-level planning is increasingly asked for, primarily due to concerns about increasing habitat fragmentation and its negative impact on biodiversity (Forsberg 2012, Andersson *et al.* 2013, Henriksson 2017). At the regional level, green infrastructure planning is being implemented to create functional habitat networks for biodiversity conservation (SEPA 2015). In this process, the value of resilient ecosystems for the provision of important ecosystem services is emphasised. How this type of planning will influence forest planning is not clear, but the role of participation, coordination, and long-term planning horizon for the successful establishment of green infrastructure networks is emphasised (SEPA 2015, Henriksson 2017). Consequently, there is a need for forest planning activities that go beyond the property level, and that balance different forest values.

2 Objectives

The overall objective of this thesis was to develop forest management scenarios at the landscape level using different methods and considering factors such as ownership structure and the request for more varied management. In addition, this thesis evaluates how the different scenarios balance economic, ecological, and social forest values.

The following is a list of the specific objectives for each of the papers:

Paper I: The objective was to determine the proportions of non-industrial private forest owners employing different management strategies and to identify the most important factors influencing their choice of management strategy. In particular, we were interested in whether gender and residence had an effect on choice of management strategy as the share of female as well as non-resident owners is increasing.

Paper II: The objective was to test and describe a method for and the effect of considering the diversity of forest ownership structure in long-term forest scenarios.

Paper III: The objective was to demonstrate how scenario analysis at the landscape scale can be used to link potential developments in society with the provision of several boreal forest ecosystem services through assumptions about how societal developments affect forest owner behaviour. The paper also discusses the viability of the approach as an instrument for local governance.

Paper IV: The objective was to evaluate how well different forest management scenarios balance economic, ecological, and social forest values. The evaluated forest management scenarios were chosen to depict management strategies that are being advocated and discussed for meeting the challenges posed to forestry by environmental and socio-economic changes.

Paper V: The objective was to elaborate an approach for balancing economic and recreational values in a forest landscape by considering both locational aspects (e.g., population density in the vicinity) and forest structure aspects.

3 Summary of papers

3.1 Overview

After a brief description of the case study areas and Heureka forest DSS used in Papers II-V, I will summarize the five papers included in this thesis in the following sections. Table *1* gives an overview of the spatial and temporal scale as well as the methods and models used in each of the papers.

Table 1. *Overview of Papers I-V.*

Paper	Spatial scale	Temporal scale	Method used	Forest DSS used
I	National (Sweden)	Current situation	Statistical analysis of survey results	-
II	Landscape (Hässleholm and Vilhelmina municipalities)	20 and 100 years	Simulation	Heureka RegWise
III	Landscape (Vilhelmina municipality)	30 and 90 years	Optimization	Heureka PlanWise
IV	Landscape (Hässleholm and Vilhelmina municipalities)	100 years	Simulation and MCDA	Heureka RegWise and PlanEval
V	Landscape (sub-area in Hässleholm municipality)	50 years	Optimization	Heureka PlanWise

3.1.1 Case study areas

There are different ways to define and outline landscapes, including ecological units and administrative boundaries (Raudsepp-Hearne *et al.* 2010, Englund *et al.* 2017). In Sweden, local planning occurs on municipality level, which makes this spatial level relevant for planning problems that can be used as input for local governance. The size of municipalities varies greatly between different parts of the country, but most municipalities include a considerable number of forest properties and variation in site types, making the results relevant even for other areas with similar forest ownership structure and growing conditions. Two contrasting municipalities were used as case study areas in this thesis: Vilhelmina in northern Sweden and Hässleholm in southern Sweden (*Figure 2*). The case study areas differ in terms of size, population, growing conditions, and forest ownership structure (Table *2*).

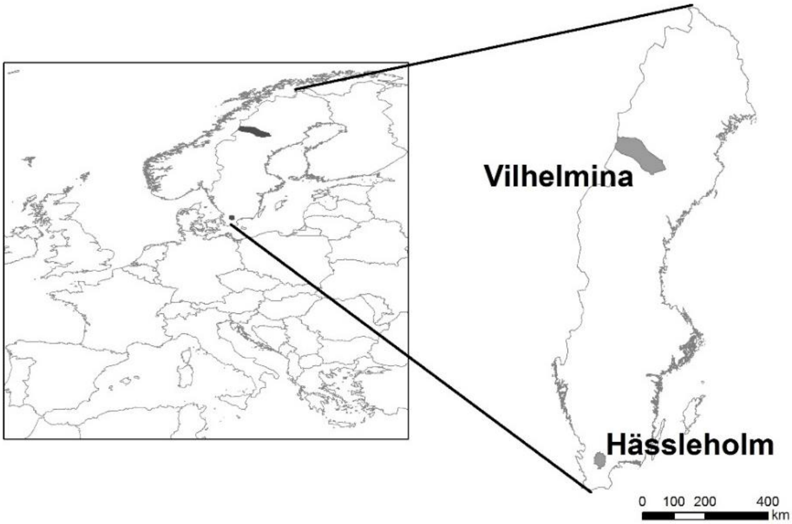


Figure 2. Location of the case study areas: the municipalities of Vilhelmina and Hässleholm.

Table 2. *Key facts about the case study areas.*

	Hässleholm	Vilhelmina
Total area (1000 ha) (SCB 2015a)	131	874
Inhabitants (SCB 2015b)	50,565	6848
Biogeographical region (EEA 2015)	Continental	Boreal/Alpine
Productive forest area (1000 ha)	73	315
Forest ownership (%)		
NIPF	86	39
Private-sector enterprise[(1)]	3	22
State	0	26
Other	11	13

(1) Including Sveaskog, a state-owned enterprise.

Input data for the Heureka DSS, which were used in Papers II-V, consisted of stand level forest data, which was created using a country-wide forest map based on satellite data and NFI field data (Reese *et al.* 2003), and complemented with information from NFI plots, cadastral maps (Metria 2014), as well as a number of relevant environmental and administrative layers, such as key biotopes, nature reserves, Natura 2000 areas, bog forests, and zones where only continuous cover forestry is permitted (Naturvårdsverket 2015, Skogsstyrelsen 2015a, 2015b). According to the input data, Hässleholm has a productive forest area of about 73,000 ha consisting mainly of Norway spruce (50%), European beech (14%), birch (11%), and Scots pine (9%). The productive forest area in Vilhelmina is

315,000 ha and consists mainly of Norway spruce (57%), Scots pine (27%), and birch (13%).

In Papers II and IV, both municipalities were used as case study areas. In Paper III, only Vilhelmina was included. In Paper V, a sub-area of Hässleholm (about 300 km^2) was used as the case study area.

3.1.2 The Heureka forest DSS

The Heureka forest DSS was developed at SLU and released in 2009 (Wikström *et al.* 2011). Today, this DSS is widely used in Sweden in research, at forest companies, and as a service for forest owners. The Heureka system includes three applications that are designed to be used at different spatial levels and includes one application that helps compare forest plans using MCDA. *StandWise* is an interactive simulator for stand-level analysis. *PlanWise* is a forest planning tool that uses optimization to find good plans based on the management objectives of the forest owner. *PlanWise* is designed for medium and large forest properties and can even be used at the landscape scale. *RegWise* is a simulation model that is especially suitable for long-term scenario analysis on larger scales (landscape up to national level). *PlanEval* is a MCDA application designed to evaluate and rank forest plans or scenarios created in *PlanWise* or *RegWise*. PlanEval is recently also available in a web version intended for participatory planning processes.

At the core of the model suite are a set of empirical growth and yield models that project the tree layer development, including models for stand establishment, diameter growth, height growth, in-growth, and mortality. These models are based on data from the National Forest Inventory, long-term experiments, and yield plots and are typically developed using regression analysis (Fridman and Ståhl 2001, Wikberg 2004, Fahlvik *et al.* 2014). Using results from process-based models, researchers and other users can adjust the empirical growth models to account for expected climate change effects.

The user can define a large number of different forest management options, such as management systems (unmanaged, even-aged, and uneven-aged), type of regeneration, regeneration species, timing and intensity of thinnings, fertilization, and extent of nature conservation efforts, including the area set-aside during harvesting and the number of high stumps and retention trees left on the felling site. In *PlanWise* and *RegWise*, different management options can be defined for different forest types to distinguish, for example, between tree species or owner categories. In *PlanEval*, the user can choose between different methods for evaluating and ranking the plans. AHP and SMART are available both for eliciting weights for the objectives and for weighting the alternatives. In addition to these two methods, value functions can be used for setting weights to the different alternatives. It is possible to include multiple decision-makers. Decision-making problems can be published on a website so decision-makers, experts, and stakeholders can evaluate plans or scenarios online. The main user can choose which parts of the decision-making problem online users have access to (i.e., the objectives and criteria that can be weighed by each online user).

3.2 Factors influencing the choice of management strategy among small-scale private forest owners in Sweden (Paper I)

Paper I investigated the distribution of management strategies among NIPF owners and which factors influence the choice of strategy. This investigation was done by analysing a nation-wide postal survey of NIPF owners, which was sent to 2100 forest owners in 2012. The survey was designed within the Swedish research project PLURAL (Planning for rural-urban dynamics: living and acting at several places) and conducted by Statistics Sweden. The response rate was 60.1%. In addition to socio-economic questions, the questionnaire included questions about the forest property, the owner's view on forests, and their forest management activities. Forest owners were asked to choose which forest management strategies best described their management activities. The forest owners had a choice of five strategies (short names in parentheses not shown to respondents):

- Strategy 1: I thin and clear-cut only on a small scale. I let the forest grow old, but I do not expect the harvest to increase in the future. (*Passive*).
- Strategy 2: I harvest only on a small scale, so that the amount of old forest remains constant or increases. My management practices are oriented towards nature protection, for example to increase the proportion of broadleaved forest. (*Conservation*).
- Strategy 3: I harvest a lot of wood by thinning, and I clear-cut as soon as the forest age permits. (*Intensive*).
- Strategy 4: I manage the forest for increased productivity and future harvest opportunities. Examples of my management practices are planting with soil scarification, pre-commercial thinning, ditching, and fertilization. (*Productivity*).
- Strategy 5: I harvest carefully and my management practices aim to increase harvest opportunities in the medium term. (*Save*).

Factors considered in the study included hard factors such as socio-economic factors, residence (resident owners live in the same municipality where their forest property is located and non-resident owners live in another municipality), and property size. Soft factors included interest in and knowledge about forestry, ownership objectives, and the importance of economic income from the property. To test for differences in management strategies among the factors, we used Pearson chi-square tests of independence for categorical factors and analysis of variance tests for quantitative factors.

The results of Paper I illustrate that a large proportion of forest owners employ management strategies that do not have a traditional wood production-oriented focus. Almost one-third of all owners chose the *Save* strategy and around one-quarter the *Passive* strategy (Table *3*). The *Conservation* and *Intensive* strategies were less prevalent. The proportion of owners choosing strategies with a main focus on wood production and economic income from forestry (*Productivity* and *Intensive*) was 36%.

Table 3. *Proportions of owners employing different management strategies in northern and southern Sweden and overall (total).*

Strategy	North		South		Total	
	# owners	%	# owners	%	# owners	%
Passive	207	26.0	78	21.0	285	24.4
Conservation	61	7.6	42	11.2	102	8.8
Intensive	53	6.7	45	12.1	98	8.4
Productivity	231	29.0	93	25.0	324	27.7
Save	244	30.7	114	30.7	359	30.7
Total	797	100.0	372	100.0	1169	100.0

The impact of gender and residence on the choice of management strategy was small, the most influential factor being property size. Owners of larger properties more often chose the *Productivity* strategy, whereas the *Passive* strategy was more common among owners of small properties (Table *4*). As small properties make up a minor proportion of the forest area owned by NIPF owners, the share of the forest area managed with a clear focus on timber production (*Intensive* and *Productivity* management strategies) is larger than the proportion of owners employing these strategies.

Owners who chose the *Productivity* strategy were more interested in and more knowledgeable about forestry issues and attached more importance to economic income from forestry, compared to owners who chose the *Passive* strategy. We conclude that the variety in management strategies among NIPF deserves more attention and should not be neglected in long-term forest resource projections.

Table 4. *Proportion of owners employing the various management strategies for different property size classes and the proportion of productive forest area owned by NIPF owners within each size class.*

	Management Strategy					Proportion of productive forest area owned by NIPF owners[1]
Property size (ha)	Passive	Conservation	Intensive	Productivity	Save	
6-20	35%	12%	4%	10%	38%	10%
21-50	27%	7%	12%	26%	28%	20%
>50	13%	7%	10%	45%	26%	68%

1 Source: (Swedish Forest Agency 2013)

3.3 Accounting for a diverse forest ownership structure in projections of forest sustainability indicators (Paper II)

Paper II took up the results from Paper I and assessed the effect of a diverse ownership structure with varying management strategies among and within ownership categories on the outcome of long-term projections of forest sustainability indicators. To do this, two long-term scenarios were simulated and compared: one scenario considered the diversity of management strategies (Diverse) and one did not (Simple). In the Simple scenario, different management strategies were applied for NIPF owners and other owners, largely based on the reference scenario in a nation-wide forest impact analysis (SLU and Skogsstyrelsen 2008). In the Diverse scenario, we implemented five different management strategies for NIPF owners based on Paper I, and applied more differentiation to other owners. The scenarios were simulated in the Heureka RegWise simulation model. RegWise was applied in a spatially explicit mode, projecting the development of individual stands. Two contrasting municipalities were used as case study areas in this paper: Vilhelmina in northern Sweden and Hässleholm in southern Sweden (for details, see section 3.1.1).

The outcome of the scenarios was compared for a number of economic, ecological, and social indicators (Table *5*).

Table 5. *Description of the indicators used to compare the scenarios in Paper II.*

Indicator	Description
Economic	
Total harvest (1000 m^3 over bark/year)	Annual volume harvested in final fellings, thinnings, selective fellings, shelterwood fellings, and seed tree removal.
Net present value (SEK)	Sum of the present values of benefits and costs over 100 years with an interest rate of 1.5%.
Growing stock (m^3/ha)	Mean standing volume of living trees, above stump, over-bark.

Growth (m^3/ha/year)	Net annual volume increment (growth–natural mortality).
Potential reindeer winter pasture (%)	Share of productive forest area that is potentially available for reindeer winter grazing according to an indicator developed by Korosuo *et al.*(2014).
Ecological	
Mature forest with high share of broadleaves (%)	Proportion of productive forest area with a mean stand age of more than 60 years in Hässleholm, and more than 80 years in Vilhelmina, where broadleaves make up at least 25% of the basal area. These forests are also valuable for recreation.
Old forest (%)	Share of productive forest area with a mean stand age of more than 120 years in Hässleholm and more than 140 years in Vilhelmina. Old forest is also valuable for recreation.
Large diameter trees (trees/ha)	Density of trees with a diameter >40 cm at breast height.
Fresh deadwood (m^3/ha)	Deadwood with a diameter >10 cm, with a very low level of decomposition: decay classes 0 and 1 according to the Swedish National Inventory (NFI, 2014).
Social	
Sparse forest (%)	Proportion of productive forest area with less than 1000 stems per ha and a mean stand height > 10 m.
Clear-cut area (%)	Proportion of productive forest area that is subject to clearcutting annually (excluding regeneration areas with seed or shelter tree retention).
Person-years (years)	Number of person-years (full-time employment, 1800 h work/year) needed for forest management activities (including soil scarification, planting, pre-commercial thinning, thinning, selective cutting, final felling, shelterwood/seed tree removal, timber transport to road-side).

The results revealed that scenario differences were considerable already after a medium-term of 20 years (Figures 3 and 4). In both municipalities, harvest volume was lower for the Diverse scenario than for the Simple scenario. Consequently, the Diverse scenario had a higher growing stock, whereas growth was hardly influenced. The ecological and most of the social indicators profited from the lower harvest level in the Diverse scenario. However, the number of person-years was lower in Diverse compared to Simple.

As the Diverse scenario was parameterized based on a subjective interpretation of the NIPF owners' management strategies, the sensitivity of the results to changes in the most influential parameters was tested by creating two alternatives for the Diverse scenario. One of the alternatives featured more intensive and the other less intensive forest management, aiming to cover a considerable but still plausible range of parameter settings.

The results of the sensitivity analysis revealed that several indicators, especially the ecological ones, were highly sensitive to changes in parameter settings, with large differences in indicator outcome between the two alternatives to the Diverse scenario. However, a considerable difference in indicator outcome compared to the Simple scenario remained for both alternatives.

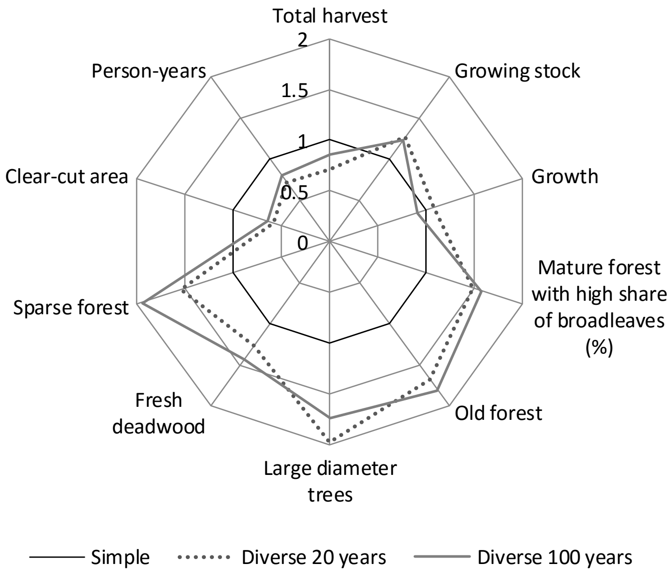


Figure 3. Ratio between the Diverse and the Simple scenario after 20 and 100 years of simulation for Hässleholm with Simple as reference (Simple = 1). For Total harvest, Growth, and Clear-cut area, the ratio between the averages for the first and the last 20 years of simulation was used. (modified from Paper II).

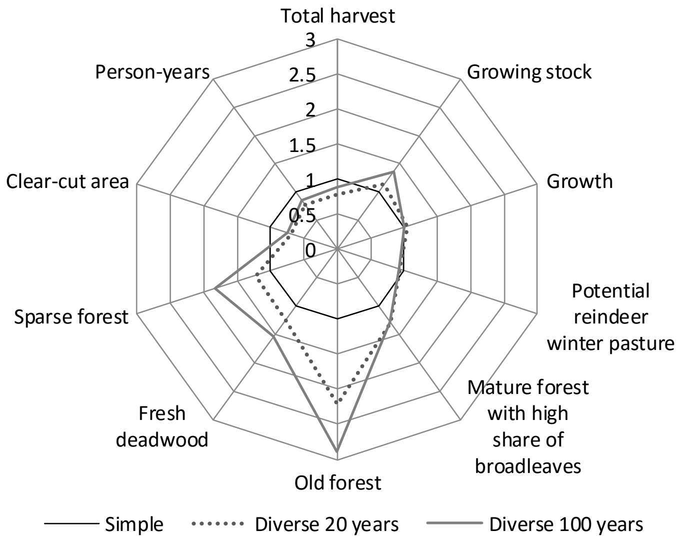


Figure 4. Ratio between the Diverse and the Simple scenario after 20 and 100 years of simulation for Vilhelmina with Simple as reference (Simple = 1). For Total harvest, Growth, and Clear-cut area, the ratio between the averages for the first and the last 20 years of simulation was used. The results for large diameter trees are not included as there were very few such trees in the beginning of the simulation in Vilhelmina, making scenario comparisons very uncertain (modified from Paper II).

3.4 Modelling ecosystem services and forest owner behaviour through scenario analysis on a landscape level (Paper III)

Using Vilhelmina municipality as case study area, Paper III presents an alternative method of accounting for forest owner behaviour in scenario analysis on the landscape level. Whereas Paper II directly parametrized different management strategies of NIPF owners, Paper III starts from different owner types who apply a varying mixture of different management regimes to their properties. The management regimes range from no management to intensive and production-oriented management and include traditional even-aged management regimes as well as continuous cover forestry. In addition to a business-as-usual (BAU) scenario illustrating a continuation of current practices, three future scenarios were implemented and compared based on qualitative scenarios developed and described in Carlsson *et al.* (2015):

(1) "Fade Out" assumes that the decrease in the municipality population continues, wood production in the region is challenged by strong

competition from other parts of the world, and high transportation costs are present due to long distances to industries and consumers.

(2) "Rural diversity" assumes that forestry has undergone a paradigm shift towards truly multipurpose forest management with an increased interest in leaving the city for a better life in the countryside, increased interest in forest ownership, and a greater degree of self-sufficiency.

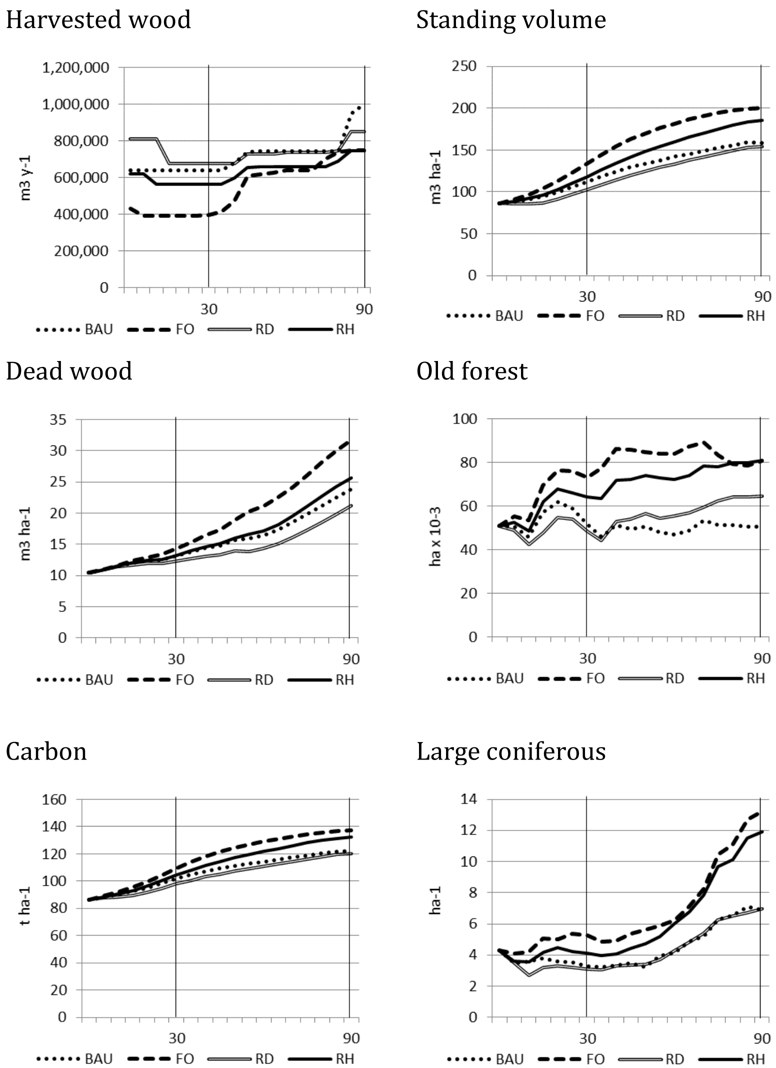
(3) "Reindeer husbandry" assumes strengthened rights for the Sámi people, leading to more consideration for the needs of reindeer husbandry in forest management.

From a forest management perspective, the scenarios differ in the composition of forest management regimes that are applied by the different owner categories and in the share of forest area owned by different owner types. For example, in the "Fade out" scenario it was assumed that the share of forest owned by private companies increases considerably, with a decrease in NIPF ownership, and that forests are managed less intensively compared to today. In the "Rural diversity" scenario, on the other hand, it was assumed that ownership patterns do not change although most forest owner types apply a more even distribution of forest management regimes compared to BAU. In "Reindeer husbandry", it was assumed that the share of state-owned forests increases and forest management shifts towards longer rotations compared to BAU. All three scenarios cover a time frame of 90 years.

Instead of modelling the development of the forest and related ecosystem services for each forest stand as in Paper II, the modelling in Paper III was done on the NFI plot level, which greatly reduced the computational effort needed. For each management regime, a set of treatment schedules was generated in Heureka PlanWise (Wikström *et al.* 2011) on the NFI plot level. The treatment schedules were then put into an external linear programming model that replicated the assumed forest owner behaviour under the ownership structure given by the different scenarios.

For the four scenarios, the development of nine indicators representing important ecosystem services was compared: harvested wood, standing volume, reindeer area, dead wood, old forest, number of large coniferous trees, deciduous area, deciduous volume, and carbon (*Figure 5*). The volume of harvested wood was lowest in the "Fade Out" scenario, so the outcomes for the other ecosystem services were higher compared to the other scenarios. "Rural development", on the other hand, featured the largest volume of harvested wood, with a lower outcome for the other services compared to the other scenarios over most of the modelled time frame. The other two scenarios were in-between "Fade Out" and

"Rural development", with BAU being closer to "Rural development" and "Reindeer husbandry" closer to "Fade Out".



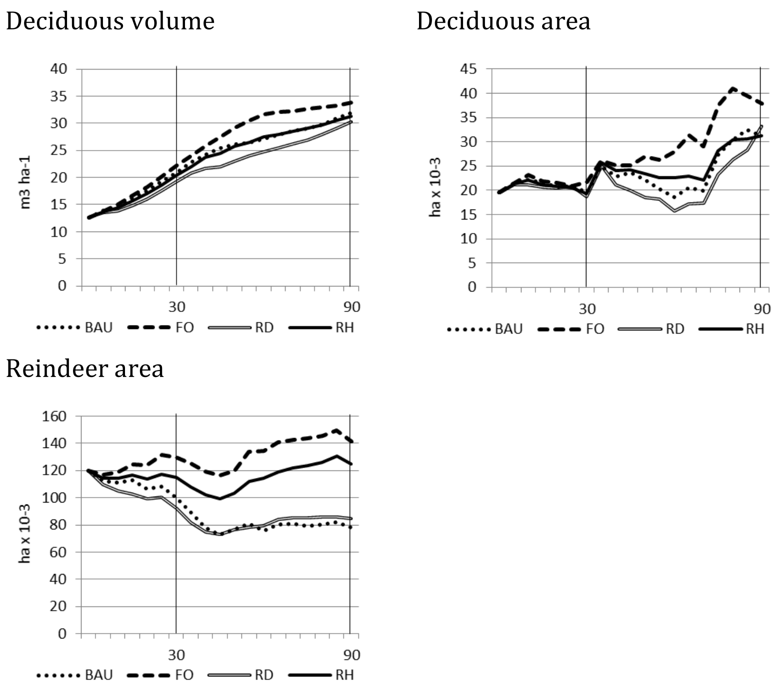


Figure 5. Development of ecosystem service indicators for scenarios "Fade out" (FO), "Rural diversity" (RD), and "Reindeer husbandry" (RH) over the time horizon (years 30 and 90 marked).

3.5 Balancing different forest values: Evaluation of forest management scenarios in a multi-criteria decision analysis framework (Paper IV)

Several forest management options have been put forward to meet the increasing challenges that forestry is facing, including the growing wood demand due to socio-economic changes, climate change mitigation and adaptation, and the increased competition between different forest functions. Paper IV evaluates ten forest management scenarios, which were designed to cover management options pertinent to the current debate on forest management diversification in a MCDA framework for two contrasting Swedish municipalities, Vilhelmina and Hässleholm (for a description of the forest input data, see section 3.1.1). The evaluation includes economic, ecological, and social aspects of sustainable forest management as well as reindeer husbandry aspects. In addition to a business-as-usual scenario (BAU), designed as a continuation of today's management practices, the scenarios included the following management options: changed share of forest set-aside for nature conservation, changed rotation periods, changes in thinning regime, increased admixture of broadleaves, higher share of continuous cover forestry, and more extensive plantation of exotic tree species as well as more fertilization (Table *6*).

Table 6. *Management scenarios evaluated in the MCDA framework.*

Scenario	**Set-asides**	**Rotation period**	**Thinnings**	**Admixture of broadleaves**	**Management regime**
Business-as-usual (BAU)	Current level	According to Forestry Act	Several	15-20%	Predominantly final felling
More set-asides (SA)	+50%	According to Forestry Act	Several	15-20%	Predominantly final felling
Longer rotation periods (RP+)	Current level	+20%	Several	15-20%	Predominantly final felling
Shortened rotation periods (RP-)	Current level	-20%	Several	15-20%	Predominantly final felling
More broadleaves (BL)	Current level	According to Forestry Act	Several	40%	Predominantly final felling
More continuous cover forestry (CCF)	Current level	According to Forestry Act	Several	15-20%	20% CCF
Climate change adaptation (CC)	Current level	-20%	One	40%	20% CCF
Increased nature conservation (NC+)	+50%	+20%	Several	40%	20% CCF
Strongly increased nature conservation (NC++)	+100%	+50%	Several	40%	20% CCF
Intensive management (Int)	-50%	-20%	One		Predominantly final felling, plantation only, more exotics, fertilization

The scenarios were simulated with the RegWise module of the Heureka forest DSS for a time horizon of 100 years. Experts in economic, ecological, and social forest values were invited to evaluate indicators connected to their field of expertise using a web-based MCDA tool (Heureka PlanEval) by creating value functions for each indicator and rating the relative importance of the indicators using the SMART method. Several of the experts evaluated both case study areas. The experts' evaluation was then used to rank the scenarios for different weight schemes in which the economic, ecological, and economic aspects of SFM were given different weights (Table *7*). There were four different weight schemes in which all weight was given to either economic, ecological, social values, and reindeer management, and two different weight schemes interpreting the Swedish Forestry Act that gives equal priority to production and environmental goals and requires certain consideration for social forest values and reindeer husbandry (Regeringen 1992). Average indicator results after 80 to 100 years of simulation were used as input for the scenario ranking to assess the long-term effects of the scenarios.

Table 7. *Weight schemes used to evaluate the scenarios.*

Weight scheme	Economic	Ecological	Social	Reindeer husbandry
Production only	1	0	0	0
Biodiversity only	0	1	0	0
Recreation only	0	0	1	0
Reindeer husbandry only	0	0	0	1
Forestry Act a	0.5	0.5	0	0
Forestry Act b	0.5	0.3	0.2 (0.1)[1]	0 (0.1)[1]

[1] In parentheses: Vilhelmina

There were no large differences in value functions between experts and municipalities, and the resulting scenario ranking was similar in both case study areas. The scenario with intensive forest management (Int) ranked highest for the “production only” weight scheme, while the scenario with strongly increased nature conservation (NC++) ranked highest for all other weight schemes, including both weight schemes interpreting the Swedish Forestry Act. In all weight schemes except “production only”, scenarios with more nature conservation, more CCF, longer rotation periods, and more set-asides ranked higher than BAU. The results thus illustrate that there is a clear trade-off between economic values on the one hand and ecological, social, and reindeer husbandry values on the other, suggesting that current management practices in Sweden prioritize economic aspects over ecological forest values. Scenarios with more continuous cover forestry, a larger share of set-asides, and longer rotation periods would be beneficial not only for ecological forest values but also for recreational values and reindeer management. Expert participation through the web tool worked well in this study and was shown to be a promising alternative to physical meetings, which require a greater commitment in terms of time and resources.

3.6 Balancing landscape-level forest management between recreation and wood production (Paper V)

The importance of forests for outdoor recreation is widely acknowledged. Intensive forest management is often in conflict with recreational forest values, and tools are needed that help to balance wood production and recreational values in landscape-level forest management. In this paper, an approach is elaborated that includes a model for calculating the recreational value of the forest landscape in a forest DSS, and tested for a case study area in southern Sweden (a part of Hässleholm municipality), with almost 14 000 ha of productive forest area. By including the recreational value in a set of mixed integer optimisation models, different management strategies are strategically distributed throughout the landscape for different levels of consideration for recreation. The recreational model combines locational aspects, such as population density in the vicinity, with forest structure aspects in a landscape recreation index:

$$R_p = L * S_p$$

where R_p is the landscape recreation index for period p, L is the location index, and S_p is the forest stand index for period p. All indices are calculated on the stand-level. The location index L is based on an expert model and gives a value between 1 and 0, where a value close to 1 indicates that the forest is potentially very valuable for recreation for a large population. The most important factor in the model is the number of people living within walking distance; other factors include nearness to water and disturbances by big roads. The forest stand index model was based on recreational preference studies, and includes a number of forest variables such as the number of small, medium and large stems, tree species distribution, and degree of soil damage. It is designed to give values between 1 and 0, where values close to 1 indicate that the forest stand is potentially very suitable for recreation.

The Heureka PlanWise model was used to project forest structure for different management strategies over time and to distribute the management strategies throughout the landscape using optimisation. The model for calculating the forest stand index S_p is included in Heureka PlanWise. The location index L was calculated in a GIS software (ArcGIS 10.4.1) and its values were imported into PlanWise together with the forest input data. While the location index L was assumed to be constant over time, the development of forest structure and the resulting forest stand index is projected over time under different management strategies. The management strategies include production-oriented management, strategies with prolonged rotation periods

(25% and 50% prolongation), continuous cover forestry, shelterwood regeneration, and no management. A set of alternative treatment schedules, i.e., a sequence of treatments such as thinning and final felling, was created for each stand and for all applicable management strategies. When generating the treatment schedules, we applied a 2% real discount rate to calculate the net present value (NPV) of costs for silvicultural and harvesting activities and incomes from timber and forest fuel. The time frame was 50 years and ten five-year time steps were used. A set of mixed integer optimization models were then used to distribute the treatment schedules (which are associated with the applied management strategies) throughout the landscape for different levels of consideration for recreation. In the optimization, R_p was aggregated over the whole landscape and the 50-year time frame (R_{tot}). The optimization models included one where R_{tot} was maximized, and a set of models where NPV was maximized, step-wise reducing the minimum requirement for R_{tot} from 99% of the maximum R_{tot} until the restriction did not affect the outcome anymore. Four of the optimization models were chosen for further analysis: the model where R_{tot} was maximized (max R), the model where NPV was maximized with no restriction on R_{tot} (max NPV), and two models where NPV was maximized with a restriction of minimum R_{tot} of 0.9 and 0.95, respectively (labelled R 0.9 and R 0.95).

Results suggest that increasing the recreational value of the landscape reduces potential NPV. However, at a loss of merely 3.8% of potential average NPV, as much as 95% of the maximum potential recreation index can be achieved if management changes are placed strategically throughout the landscape (*Figure 6*).

In the max NPV scenario, the most prevalent management strategies were the 25% longer rotations strategy, the production-oriented strategy, and the continuous cover forestry (CCF) strategy, with about one-quarter of the area each (*Figure 7*). With increasing consideration for recreation, the production strategy was gradually replaced, predominantly with the 50% longer rotations strategy. Maximizing R_{tot} led to a drastic change in the distribution of management strategies compared to the scenario where 95% of potential R_{tot} was attained; in the max R scenario, most of the forest area is left with no management or assigned the 50% longer rotations strategy, with more than 40% of the area under each of these two strategies.

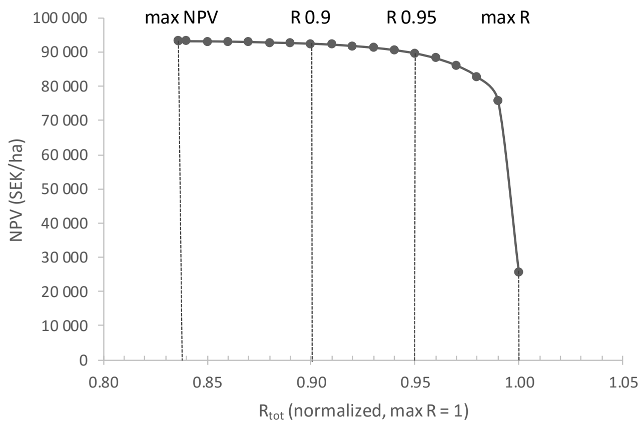


Figure 6. Relationship between NPV and R_{tot}. The loss in NPV was 0.8% for R 0.9, 3.8% for R 0.95 and 72% for max R.

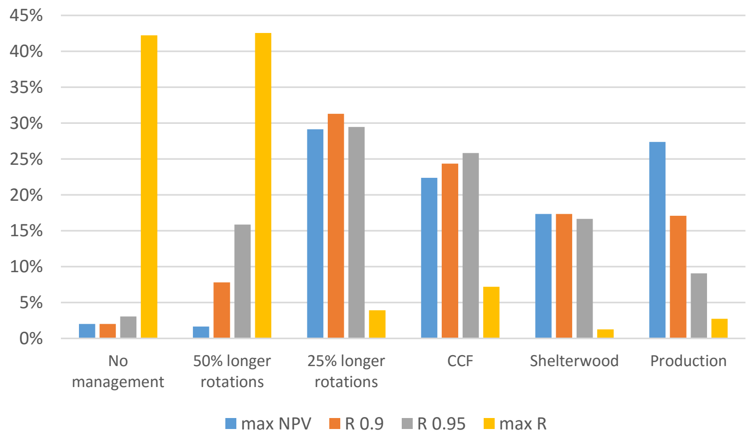


Figure 7. Area proportion per management strategy for the scenarios max NPV, R 0.9, R 0.95, and max R.

4 Discussion and Conclusions

4.1 Accounting for forest ownership structure

One of the starting points of this thesis was the question of forest ownership structure: What impact can the ongoing changes in private forest ownership, such as the increasing share of female and non-resident owners, be expected to have on forest management and the resulting ecosystem services? Paper I suggests that gender and distance to the forest property have little influence on the management strategy of a forest owner, but property size was shown to be more important. These results suggest that the ongoing changes in the NIPF ownership probably do not have sizeable impacts on forest management, at least in the near future. Furthermore, most forest owners surveyed in Paper I indicated that they don't employ a traditional production-oriented management strategy, but rather save the forest for later or do not manage the forest very actively. However, a sizable share of the forest area owned by NIPF owners is still managed using the production-oriented strategy due to the higher prevalence of the production-oriented strategy among owners of larger properties compared to smaller properties. A weakness in the study design of Paper I was that the choice and wording of the management strategies included in the survey were not tested before including them in the survey due to time constraints. It would have been beneficial to discuss strategy formulation with a small sample of forest owners to get a feeling for possible ambiguity and different potential interpretations of the strategies and to have a chance to adapt the wording accordingly. The main conclusion of this study – that property size has a considerable impact on management strategy with owners of larger properties more often managing their forest production-oriented compared to owners of small properties – agrees with several other studies (see Hatcher *et al.* (2013) for a detailed literature review of the forest holding size problem). The findings from Paper I imply that the variety in management strategies among forest owners, an often-ignored fact in projections of forest ecosystem services, deserves more attention in future assessments. This raises the question about ways to incorporate owner behaviour in forest DSS. The objectives of forest owners have been studied extensively in many countries with the implicit assumption that owners' objectives have a bearing on management. However, the link between owner objectives and actual forest management was seldom analysed explicitly (Dhubháin *et al.* 2007). The few existing studies found that objectives affect harvest decisions to some extent, even though the link between objectives and harvesting behaviour is not straightforward (Kuuluvainen *et al.* 1996, Karppinen 1998, Favada *et al.* 2009). Although management objectives have been shown to be stable for individual owners (Karppinen 1998), it is conceivable that their link with harvesting behaviour is not because forest management depends not only on owners' objectives, but also on, for example, the local context and social norms (Wallin 2017). Additionally, forestry advisors, contractors, and timber buyers also influence forest owners and forest management (Holmgren 2015, Carlsson 2017). These factors are less well studied and their impact on management behaviour is therefore difficult to quantify. Instead of categorizing forest owners according to their objectives and making assumptions about the link between objectives and management, Paper II used the distribution of management strategies of NIPF owners from Paper I. The comparison of a scenario where the management strategies were implemented (Diverse), along with management specifications for other owner categories, with one where the variety in management behaviour was largely ignored (Simple) revealed considerable differences in many economic, ecological, and social indicators. Results from Paper II thus suggest that disregarding the differences in forest management between different owners may lead to considerable over- and under-estimations of important ecosystem services, both in medium and long-term analysis. Arguably, implementing the management strategies from Paper I into a forest DSS required a subjective interpretation of management strategies. However, the results of the sensitivity analysis indicate that differences remain even if the parametrization of the strategies is changed. However, potential management changes over time, e.g., due to generational change in ownership were not considered. Although the results should be interpreted in the light of these uncertainties, they highlight the importance of dealing with the diversity in management practices among forest owners in medium and long-term analysis. The results also illustrate that many indicators of important ecosystem services seem to be sensitive to harvest volume and thus management intensity, thus demonstrating a trade-off between wood production on the one hand, and biodiversity and recreation on the other.

Paper III presents another way to account for ownership structure in long-term analysis and develops and analyses scenarios that link potential societal developments and their impact on forest owner behaviour with forest ecosystem service provision. Paper III defined different owner types, which combine objectives and management preferences, thus presenting an intermediate method between focusing on objectives and management strategies. In contrast to Paper II, where each owner was assigned one out of five management strategies, Paper III allowed owner types to apply a mixture of management regimes. This is reasonable, as in practice forest owners may have different objectives with different parts of their forest property. The distribution of management regimes in the business-as-usual scenario was largely based on Paper I. The approaches used in Paper II and, to some degree, in Paper III therefore depend on how well forest owners assess their own management strategy and how well the management strategies are reproduced in the parametrization of the forest DSS.

A more objective basis to account for the divergent management behaviour of different forest owners could be to study NIPF owners' actual management activities. This can be done, for example, by surveying an adequate sample of forest owners or by combining observations from forest inventories with ownership classes and then to analyse the differences in management behaviour between different owner categories. Both of these approaches have been used in Sweden (Holm and Lundström 2000, Berg Lejon *et al.* 2011, Lidestav and Berg Lejon 2013). However, these options face one shared difficulty: they illustrate the behaviour of the current owners but are of uncertain validity regarding future ownership changes. Due to the relative high average age of forest owners in Sweden (Haugen *et al.* 2016), many properties will get new owners during the coming years, and the situation is similar in other forest-rich countries. However, little is known about the forest-related values and management styles of the future forest owners (Kronholm and Wästerlund 2016).

4.2 Balancing different ecosystem services

Both Paper II and III illustrate that harvest levels and management intensity affect many important ecosystem services. At the same time, there is an increasing interest for more diversity in forest management practices, so there is a need to assess different practices from all aspects of sustainability and to evaluate how well the different options manage to fulfil policy goals. To address these needs, Paper IV evaluates how economic, ecological, and social forest values are balanced by analysing and evaluating ten management scenarios. The results suggest that several management scenarios would be better suited to fulfil the co-equal production and environment objective in the Swedish Forestry Act compared to a continuation of current practices and illustrates a clear trade-off between economic values on the one hand, and ecological, social, and reindeer husbandry values on the other. The co-equal production and environment goal in Swedish forest policy has been in place for more than 20 years, and even though environmental consideration has increased considerably since then, the results in Paper IV as well as other research (Lindahl *et al.* in press, Forsberg 2012, Holmgren 2015, Wallin 2017) suggest that production values generally have a higher weight in management decisions compared to environmental values. Forest governance research suggests that this may be because goal conflicts are insufficiently dealt with in policy making in Sweden, as the responsibility for dealing with stand-level trade-offs is left to the forest owner

(Lindahl *et al.* in press). Swedish forest governance builds largely on soft governance instruments, such as advice and information, for goal achievement and expects forest owners to consider nature and social forest values in their management to a greater degree than required by the legislation. However, it has been shown that information and advice may not be enough to ensure changes in forestry. Factors such as uncertainties regarding environmental change and alternative management practices, path dependency after decades of production-oriented, strictly regulated forestry, as well as perceived risks and costs related to changes in well-established management practices can combine to create inertia in forest management practice (Lidskog and Sjödin 2014, Uggla and Lidskog 2015). The results in Paper IV and similar studies can therefore provide valuable input in the shaping of new forest policy instruments. It should however be noted that the business-as-usual (BAU) scenario, designed to represent a continuation of current management practices, does not explicitly consider the variation in management strategies among different owners identified in Paper I. Instead, average probabilities of future management activities based on observed management from National Inventory Plots (Holm and Lundström 2000) are used to define management priorities. However, more factors determining forest management are included in the definition of the BAU scenario in Paper IV compared to the Simple scenario in Paper II, including voluntary set-asides and nature-conservation oriented management in specified areas. It can therefore be supposed that the BAU scenario of Paper IV is a better approximation of current management practices than the Simple scenario in Paper II.

In Paper IV, the evaluation process did not consider the spatial distribution of forest values. Compared to economic and ecological values, recreational values proved to be more difficult to evaluate in general terms as they are very location-dependent. Paper V addresses this problem by elaborating and testing an approach for balancing economic and recreational values in a forest landscape, combining locational aspects with forest structural aspects. Results suggest that recreational forest value can be improved with relatively low economic loss by strategically distributing different management strategies throughout the landscape. Including the potential demand for recreation through locational aspects, where population density was the most important factor, was crucial for the distribution of the management strategies by the model. By including locational aspects, management strategies that result in higher recreational value of forest stands can be prioritized in areas where there is a supposed high demand for recreation. The suggested approach could be useful for municipalities as they have a responsibility to provide a good living environment for their inhabitants but also for large forest owners with an interest for improving the recreational value of their forests. Although municipalities have limited possibilities to regulate the management of forests owned by others, the model results could be used as a basis for discussion with the owners of forests that are of high recreational importance. While the approach could be improved in several ways in future applications, it clearly illustrates the usefulness of long-term landscape level analysis for examining trade-offs between different ecosystem services.

4.3 Uncertainties

As in all modelling, there are several uncertainties related to the applied methods and input data. Some weak points were already mentioned in the sections above, but a few more general issues need to be discussed here. One important factor that was not regarded in the thesis is the potential impact of climate change. Climate change is expected to increase tree growth in Sweden and to change disturbance regimes (SOU 2007). While the implementation of growth changes in the applied forest DSS, Heureka, is relatively straightforward, the impact of changes in biotic and abiotic disturbance regimes is more difficult to model due to inherent uncertainties and the stochastic nature of disturbances. However, the focus of this thesis was not climate change impacts and adaptation, but rather the impact of changes in management. Assuming that similar climate change impacts do not differ considerably between the different management scenarios, the relative difference in the analysed ecosystem service indicators between scenarios should be consistent even in the light of climate change. Furthermore, previous studies have shown that the effect of different management scenarios is much larger compared to the effect of moderate climate change scenarios (Eggers *et al.* 2008, Hengeveld *et al.* 2014).

Nevertheless, the impact of disturbances deserves more attention in the future, as disturbance risk is not only affected by climate change but also by changes in forest management. For example, longer rotation periods are likely to increase the risk for storm damage as well as root rot predominantly in mature spruce stands (Thor *et al.* 2005, Valinger *et al.* 2006, Seidl *et al.* 2011). Root rot and other damage agents cause large financial losses in forestry. While wind disturbances can be included in the Heureka simulation module RegWise, this is not yet possible in the Heureka module using optimization (PlanWise). And while it is possible to estimate the expected occurrence of root rot in Heureka, timber value losses are not calculated, so root rot does not affect the economic outcome of the projections. It is therefore possible that the projected economic outcome of scenarios with prolonged rotation periods is overestimated to some degree. This is, however, only one of the uncertainties regarding the economic projections. Other uncertainties include the development of timber prices and management costs, which, in turn, also influence management behaviour to some extent (Lönnstedt 1997, Favada *et al.* 2009).

The ecosystem services that can be assessed with help of the Heureka DSS are largely limited to those that depend on the tree layer. However, ground vegetation is also important for many services, including non-wood products, recreation, and biodiversity. Some services can be approximated using information on the tree layer. For example, the occurrence of ground lichen, which is the main reindeer winter fodder, has been connected to certain forest types (cf. Korosuo *et al.* 2014), and recently tree layer-based habitat suitability models have been integrated in Heureka for a set of species. Other services are more difficult to connect to the tree layer. A better representation of non-tree vegetation would allow for the assessment of the potential future provision of a larger number of forest ecosystem services. On a similar note, more detailed information on the initial forest conditions, such as the amounts of deadwood, would be valuable for the assessment of, e.g., biodiversity and recreation. Information on initial deadwood amounts are seldom available, and while the Heureka system allows the user to choose between different initial deadwood levels in case of lacking data, this necessitates assumptions and adds uncertainties to the projections of deadwood volumes.

4.4 Planning and decision making

In Sweden, long-term forest planning is established among large forest-owning companies and to some extent in the green forest management plans through the categorization of stands according to nature conservation ambitions. Typically, forest planning is not well integrated with other planning activities, such as municipal plans (Stjernström *et al.* 2013), and is usually done on the property level. However, planning on spatial scales larger than the property level is needed for analysing trade-offs between ecosystem services. Knowledge about trade-offs between ecosystem services and on how different management regimes affect the provision of ecosystem services is essential for better decision making in forest management and governance and for dealing with the increasing and diversifying demands on forests. Although planning activities spanning several forest properties are rare, the studies available in the literature seem promising. For example, Nordström *et al.* (2010) combined participatory planning and MCDA to create a strategic forest management plan for a municipality, covering several large forest owners and integrating the interests of different stakeholder groups. A project in southern Sweden analysed the long-term consequences of different management strategies for a multi-owner biosphere reserve. Analysis results were then successfully used in dialogue processes with forest owners with the aim to increase the share of broadleaves (Länsstyrelsen Jönköping 2017). A similar project where Heureka scenario analysis has been used as a base for a dialogue process with forest owners has been performed in northern Sweden (Länsstyrelsen Västerbotten 2011) with the aim to enhance habitat conditions of threatened species. On the national level, long-term forest management scenarios are regularly established and analysed in order to assess the consequences of different management intensities on timber flows as well as environmental and other forest values (Gustafsson and Hägg 2004, SLU and Skogsstyrelsen 2008, Claesson *et al.* 2015).

The work done in this thesis contributes to this research field and gives examples of how different modelling techniques can be used to create and evaluate long-term landscape level scenarios and to analyse trade-offs between different ecosystem services. In addition to its scientific contribution, the methods used and the results presented in this thesis can support local as well as national forest governance and decision-making.

4.5 Conclusions and future research

The papers included in this thesis clearly illustrate that long-term scenario analysis on the landscape level can be a useful tool for illustrating trade-offs between different ecosystem services, for evaluating different management practices, as well as for assessing potential future developments, and can thus provide valuable input for forest governance at different levels. In scenarios of future forest development, it will be important to consider the most important drivers. Ignoring the differences in forest owner behaviour can potentially lead to considerable over- or under-estimations of ecosystem service provision. Consequently, accounting for owner behaviour in forest ecosystem services projections deserves more attention in future analysis, and more research is needed to find suitable, cost-effective ways. In particular, very little is known about future forest owners and their views on forests and potential management behaviour. Research on forest owners should, however, not be limited to studying owners' objectives and management behaviour; research should also study the interactions with local context, social norms, and advisory strategies.

The results from Paper IV suggest that more diversified management is needed to support truly multifunctional forest landscapes. The value functions developed by the experts in Paper IV were used to rank different, pre-defined management scenarios, using a combination of simulation and MCDA. An alternative way would be to use the value function in multi-objective optimization similar to the work done by Triviño *et al.* (2017). That way it would be possible to distribute different management strategies strategically throughout the landscape, taking multiple objectives into account. It would also be interesting to test whether simple linear value functions (instead of the stepwise linear and cubic spline interpolation options used in Paper IV) would have led to the same result. Simple linear value functions do not convey the same amount of information but they do not necessarily require input from experts.

Finally, incorporating a landscape recreation index in a forest DSS to balance production and recreation forest values appears to be promising approach, which can be further developed in combination with, e.g., participatory mapping and participatory planning. It would be interesting to further elaborate and apply this approach in a real planning case together with a municipality or large forest owner interested in supporting recreational forest values.

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