Dissertationes Forestales 103

Silvicultural decisions based on simulation-optimization systems

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Academic dissertation

To be presented, with the permission of the Faculty of Agriculture and Forestry, University of Helsinki, for public criticism in Lecture Hall B2, Forest Sciences Building, Latokartanonkaari 7, Helsinki on 18 May 2010 at noon.

Title: Silvicultural decisions based on simulation-optimization systems

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Dissertationes Forestales 103

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ISSN 1795-7389
ISBN 978-951-651-295-5 (PDF)

(2010)

Publishers:
Finnish Society of Forest Science
Finnish Forest Research Institute
Faculty of Agriculture and Forestry of the University of Helsinki
Faculty of Forest Sciences of the University of Joensuu

Editorial Office:
Finnish Society of Forest Science
P.O. Box 18, FI-01301Vantaa, Finland
http://www.metla.fi/dissertationes

Cao, T. 2010. Silvicultural decisions based on simulation-optimization systems. Dissertationes Forestales 103. 48 p. Available at http://www.metla.fi/dissertationes/df103.htm

ABSTRACT

Forest management is facing new challenges under climate change. By adjusting thinning regimes, conventional forest management can be adapted to various objectives of utilization of forest resources, such as wood quality, forest bioenergy, and carbon sequestration. This thesis aims to develop and apply a simulation-optimization system as a tool for an interdisciplinary understanding of the interactions between wood science, forest ecology, and forest economics.

In this thesis, the OptiFor software was developed for forest resources management. The OptiFor simulation-optimization system integrated the process-based growth model PipeQual, wood quality models, biomass production and carbon emission models, as well as energy wood and commercial logging models into a single optimization model. Osyczka's direct and random search algorithm was employed to identify optimal values for a set of decision variables.

The numerical studies in this thesis broadened our current knowledge and understanding of the relationships between wood science, forest ecology, and forest economics. The results for timber production show that optimal thinning regimes depend on site quality and initial stand characteristics. Taking wood properties into account, our results show that increasing the intensity of thinning resulted in lower wood density and shorter fibers. The addition of nutrients accelerated volume growth, but lowered wood quality for Norway spruce.

Integrating energy wood harvesting into conventional forest management showed that conventional forest management without energy wood harvesting was still superior in sparse stands of Scots pine. Energy wood from precommercial thinning turned out to be optimal for dense stands. When carbon balance is taken into account, our results show that changing carbon assessment methods leads to very different optimal thinning regimes and average carbon stocks. Raising the carbon price resulted in longer rotations and a higher mean annual increment, as well as a significantly higher average carbon stock over the rotation.

Keywords: carbon accounting, economic returns, fertilization, forest bioenergy, optimal thinning, wood quality.

ACKNOWLEDGEMENTS

First of all, my warmest appreciation goes to the advisory group, Professor Lauri Valsta, Professor Annikki Mäkelä, and Dr. Pekka Saranpää for their invaluable multidisciplinary supervision. Thanks also to Professor Lauri Valsta for teaching me optimization modeling, to Professor Annikki Mäkelä for her help in studying forest ecological models, and to Dr. Pekka Saranpää for his help in studying the effects of thinning and fertilization on wood properties.

I am greatly indebted to the Finnish Forest Research Institute (METLA), where I conducted the first study of the dissertation in METLA project No. 3318, "Economic-ecological interactions in the sustainable use of forest resources". Thanks also to Professor Olli Tahvonen, Dr. Kari Hyytiäinen, Lic. Juhani Taipale, and Lic. Esa-Jusi Viitala for their help in the early stages of my studies.

During my studies, I was involved in several research projects. In addition to the METLA project, I had opportunities to work at the European Forest Institute (EFI) and in the PURO research consortium. Thanks go to Dr. Marcus Lindner and Ms. Jeannette Eggers for their help in modeling the cost module of the EFISCEN model (EFI SENSOR project, "Sustainability impact assessment: tools for the environmental, social and economic effects of multifunctional land use in European regions"), and to Dr. Harri Mäkinen and Dr. Tuula Jyske for their help in studying models for predicting wood properties (PURO research consortium, "Optimization of the quantity and quality of wood raw material in forest management and industrial processes").

Special thanks also go to the Graduate School in Forest Sciences (GSForest) for financing my PhD project, "Eco-economic model linkages toward timber and non-timber production", in which I developed the OptiFor computer program as a tool for optimization studies. This project benefited from the collaboration of multidisciplinary expert staff. Thanks go to Dr. Kari Hyytiäinen, MSc. Juha Laitila, Dr. Jari Liski, MSc. Henna Lyhykäinen, Professor Annikki Mäkelä, Dr. Harri Mäkinen, Dr. Taru Palosuo, and Professor Lauri Valsta for their help in developing the OptiFor simulation-optimization system.

Comments from the pre-examiners, Docent Anssi Ahtikoski and Professor Niels Strange, noticeably improved the dissertation, as did the English language editing of Stephen Stalter.

Finally, my deep gratitude goes to my former Professor Jianhui Yu at Fujian Agriculture and Forestry University for his encouragement, to my university friends Chengliang Chen, Fang Huang, Teng Wei, Zhao Lin, Chengyong Zhang, Yuan Yuan, and to my high school friends Kunsen Jiang, Jianhua Zhang, Weihui Zhang, Jianzhong Yang for their faithful support.

Helsinki, March 2010

Tianjian Cao

To my family

LIST OF ORIGINAL ARTICLES

This thesis consists of an introductory review followed by four research articles. The articles in the review are referred to by their Roman numerals. The articles are reprinted with the kind permission of the publishers.

I Cao T., Hyytiäinen K., Tahvonen O., Valsta L., 2006. Effects of initial stand states on optimal thinning and rotation of *Picea abies* stands. Scandinavian Journal of Forest Research 21: 388-398.

II Cao T., Valsta, L., Härkönen S., Saranpää, P., Mäkelä, A., 2008. Effects of thinning and fertilization on wood properties and economic returns for Norway spruce. Forest Ecology and Management 256: 1280-1289.

III Cao T., Hyytiäinen, K., Lyhykäinen, H., Valsta, L., 2009. Integrating bioenergy production into forest management optimization: energy wood from young Scots pine stands. (Manuscript).

IV Cao T., Valsta, L., Mäkelä, A., 2010. A comparison of carbon assessment methods for optimizing timber production and carbon sequestration in Scots pine stands. (Manuscript).

AUTHOR'S CONTRIBUTION

Tianjian Cao is responsible for the summary of this thesis. The OptiFor software used in articles II, III, and IV was developed by Tianjian Cao. He participated in the planning of articles I and II, and was fully responsible for conducting the calculations, analyzing the results, and writing articles I and II. In article I, Lauri Valsta provided the SMA software and the biological data. In article II, Tianjian Cao developed the log grading module for Norway spruce; Annikki Mäkelä provided the PipeQual model and the biological data for Norway spruce. In article III, Kari Hyytiäinen provided the biological data. In article IV, Tianjian Cao chose the biological data. In articles III and IV, Tianjian Cao was fully responsible for planning and writing the articles, as well as for applying OptiFor as a tool to conduct the calculations and to analyze the results.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Decision problems in forest ecosystem management

Forests have traditionally been used for producing timber, fuel wood, and non-wood forest products, as well as for hunting, preventing erosion, and providing amenities. Forest resources play multiple roles in sustainable development. Consequently, forest managers encounter a number of biological, economic, and social problems. The objectives of forest management are changing under climate change. Timber production is no longer a single objective in forest management. Questions about the relationship between wood quality, forest bioenergy, carbon balance, and forest management have long been the research interests of forest ecologists, wood scientists, and forest economists.

Forest management decisions vary depending on the objective. Conventional forest management focuses on timber yield, whereas intensive forest management involves silvicultural treatments and their effects on wood properties. Forest bioenergy production includes energy wood harvesting in addition to conventional logging. Forest ecosystem management and carbon balance take into consideration carbon sequestration and emissions. Balancing these conflicting objectives is both difficult and challenging.

Decisions in forest management can be classified according to five main levels: the tree level, the stand level, the forest level, the enterprise level, and the region/sector level (Valsta 1993). Strategic forest-level planning answers, among others, the question of the overall goal for the forest, whereas tactical stand-level planning answers the question of what actions should be performed (Pukkala 2002). Stand level decisions require more detail and data than do forest-level decisions, and thus enormous computing capability. On the other hand, such detailed data improve the quality of the solution. If a decision is based upon unknown data, the structure of the decision problem must shift to stochastic optimization as opposed to deterministic optimization (Taha 1997).

A forest stand is a geographically contiguous parcel of land considered homogeneous in terms of tree vegetation (Davis et al. 2001, p.65). As the smallest operational unit, the stand-level is the appropriate level for studying the economics of stand management activities. Stand-level decisions are traditionally classified into categories of even-aged management and uneven-aged management (Davis et al. 2001). Even-aged stand management can be formulated as the conventional Faustmann (1849) problem or modified joint production models (Hartman 1976), which can be solved numerically with great computational effort by using, for example, nonlinear programming (NLP) algorithms (Bazaraa et al. 1993).

The Faustmann (1849) approach was introduced to forest management 160 years ago. From an economic perspective, a standing forest is a particular form of growing capital (Clark 1990). Nevertheless, the biological characteristics of forest ecosystems make the prediction of the growing capital extremely complex. Forest management decisions involve complex ecological, economic, and social systems (Davis et al. 2001). Integrated simulation optimization systems provide a systematic means for adapting forest management to various objectives for the utilization of forest resources.

Forest management decisions require various ecological projection models depending on the properties of the optimization problems. Both empirical and process/mechanistic models have their advantages and disadvantages. Empirical models provide accurate predictions, but no underlying causes of productivity (Monserud 2003, Pretzsch et al. 2008). On the other hand, the predictions of empirical models may fail if the environment and forest management practices change under the changing climate (Matala et al. 2003). In contrast, process or mechanistic models offer ecological interpretations for the underlying causes of the effects of chosen treatments, but demonstrate precise predictions with difficulty (Monserud 2003, Pretzsch et al. 2008).

1.2 Silvicultural decisions

Silvicultural activities include regeneration, precommercial thinning, fertilization, commercial thinning, and rotation. This dissertation will emphasize the incorporation of silvicultural decisions other than regeneration into both empirical and process models. Economic research on silvicultural decisions typically focuses on timing and density control from regeneration to thinning and final harvesting in order to maximize long-term financial returns. Specifically, this dissertation will focus on commercial thinning density control, thinning type, rotation length, fertilization intensity, and precommercial thinning density control.

Thinning plays an important role in managing boreal forests. Assmann (1970) defined thinning as intervention in stands with a closed canopy. The purpose of thinning is to improve the quality of the current production of the stand by removing undesirable elements and favoring the best members of the stand. Davis et al. (2001) pointed out that the main decisions in even-aged management concern regeneration method, rotation length and thinnings. In the formulation of stand management optimization, final harvesting can be formulated as extreme thinning (Brodie and Haight 1985). By adjusting thinning regimes, forest management can accommodate various objectives for the utilization of forest resources.

Depending on its purpose, thinning can be classified as cleaning, selective thinning, and incremental thinning. The type of thinning is usually classified as thinning from below, thinning from above, and mechanical thinning (Assmann 1970, Brodie and Haight 1985, Kellomäki 2009). Assmann (1970) distinguished different types of thinnings for ordinary low thinning (thinning from below) and crown thinning (thinning from above) according to tree classes. Brodie and Haight (1985) specified the thinning type based on the ratio of the average diameter of the trees removed and the average diameter before thinning. Below thinning aims as much as possible to achieve a single-stage structure of the stand. In high or crown thinning, the primary attack is made upon the dominating stand; the under-crop is maintained as required for soil and stem protection. The objective of above thinning is to create a multiple-storied structure of the stand (Assmann 1970).

Several forest growth and yield studies have recognized the importance of the effects of thinning, especially early thinning and the frequency of thinning, on tree growth, crown development, and wood quality (Assmann 1970). Besides heredity, site quality, climate and silvicultural treatments, such as fertilization and thinning, influence the growth rate. Increasing the growth rate of trees due to thinning or fertilization, however, may reduce wood density, tracheid length, and cell wall thickness (Dinwoodie 1961, Petty et al. 1990, Zhang et al. 1996, Herman et al. 1998, Mäkinen et al. 2002). In Finnish forest practice, some forest owners favor heavy thinning and short rotation (Mielikäinen and Hynynen 2003, Mäkinen et al. 2005). Such a harvesting regime accelerates the growth rate, which may lead to changes in wood and tracheid properties (Jaakkola et al. 2005a,b).

Precommercial thinning is a silvicultural treatment frequently applied in conifer stands (Piene 1978, Pothier 2002, Fahlvik et al. 2005, Huuskonen and Hynynen 2006). Precommercial thinning, usually considered a costly silvicultural treatment, raises the temperature of the surface soil layers and improves stand composition and structure, thereby increasing future growth and yield. This especially benefits naturally regenerated stands in the boreal forest zone (Piene 1978, Pothier 2002).

The Kyoto Protocol to the United Nations Framework Convention on Climate Change has recognized the importance of forest ecosystem management in global warming (UNFCCC 1997). This recognition creates new outputs for the economic value of forests in addition to timber production, namely forest bioenergy and carbon sequestration. Questions about timber production and potential forest carbon benefits have been investigated for more than a decade (Richards and Stokes 2004). In multifunctional forest management, the more frequent use of energy wood and forest bioenergy incentives has already generated additional income to compensate for the cost of precommercial thinning (Hakkila 2006, Ministry of Agriculture and Forestry 2006). Larger carbon stocks in forests can be achieved by increasing rotation length, stand density, and other silvicultural treatments. Optimal thinning plays a key role in formulating an adaptation strategy of forest management to climate change.

1.3 Objectives of the dissertation

A number of new ecological models have been developed for predicting growth and yield, wood quality, and carbon balance. However, most applications of these forest models follow the scenario approach. But with simulations only, the applicability of these ecological models is obviously insufficient. The integrated approach, which links simulation and optimization models, provides a useful tool to improve scenario solutions. The latest ecological models must therefore be integrated into forest management optimization. Such model linkages are expected to deepen our knowledge of the adaptation strategies of forest ecosystem management and wood products to climate change.

The general objectives of the dissertation were: (1) to develop a simulation-optimization tool for decision-making in adaptive forest management, (2) to investigate facts affecting the optimal thinning regime and the profitability of thinning and fertilization for timber production and wood quality in Norway spruce stands, and (3) to evaluate forest bioenergy policies and carbon assessment methods for energy wood production and carbon sequestration in Scots pine stands. The specific objectives of the four studies of the dissertation were:

The main aim of Study **I** was to investigate how initial stand structures affect the optimal thinning regime and length of rotation period for even-aged Norway spruce stands. The study also investigated the impacts of the interest rate and flexibility of the thinning type on the optimal thinning regime and length of rotation period based on stand management optimization.

The purpose of Study **II** was to demonstrate, through two case studies, how to build a bridge between forest ecology, wood quality, and forest economics in Norway spruce. Case study 1 aimed to link the most recent ecological models for predicting the effects of thinning intensity and rotation length on the wood and tracheid properties of Norway spruce. Case study 2 explored the potential impacts of fertilization on the wood and tracheid properties of Norway spruce in the context of optimized nutrient addition that aims to maximize the tree growth rate. The overall objective of these analyses is to provide new knowledge of the economic returns of Norway spruce management strategies when taking into account wood and tracheid properties.

The objectives of Study **III** were: (1) to develop the simulation-optimization system OptiFor for optimizing timber and forest bioenergy production, (2) to integrate energy wood production from precommercial thinning into forest management optimization, and (3) to investigate the effects of various forest bioenergy policies on financial returns, growth and yield, as well as wood quality.

The goals of Study **IV** were: (1) to link biomass expansion factors and carbon emission models with the process-based growth model, (2) to develop the simulation-optimization tool OptiFor Carbon for timber production and carbon sequestration, and (3) to investigate the effects of carbon assessment methods on optimal stand management when taking into account both timber production and carbon sequestration.

2 REVIEW OF STAND MANAGEMENT OPTIMIZATION

2.1 Mathematical bioeconomics of the optimal management of forest resources

Faustmann (1849) introduced the discounting approach of infinite time for timber production, which has wildly served as the theoretical basis of forest management decisions (Clark 1976, 1990, Johansson and Löfgren 1985). The Faustmann (1849) formula can be easily modified to formulate joint production problems in forestry when externality benefits are the increasing function of the standing forest (Hartman 1976). The simultaneous determination of optimal thinning and optimal rotation length, however, is more complex. Clark (1976) presented an optimal control model and its analytical solution to include optimal thinning in addition to the optimal rotation problem.

The theoretical models of the Faustmann (1849) formula focused on the optimal rotation age *T* in timber production (Johansson and Löfgren 1985, Clark 1990). Clark (1990) showed that the forest growth function $f(V)$ is both positive and concave where $V = V(t)$ represents the volume at age t. The benefit of timber value $B = B(t)$ depends on the age t of the tree, c denotes the cost of felling, $B(t)$ - c represents the net value of the stand, and r denotes the interest rate. The single rotation problem is to maximize the present value (PV) of the forest (Eq. 1)

$$PV = \left[B(t) - c\right]e^{-rt} . \qquad (1)$$

Then the optimality condition (Eq. 2) is

$$\frac{B'(T)}{B(T) - c} = r . \qquad (2)$$

The perpetual period problem of timber production, the bare land value of the forest (Eq. 3), can be expressed as:

$$PV_{timber} = \frac{e^{-rt}\left[B(T) - c\right]}{1 - e^{-rt}} . \qquad (3)$$

To maximize the bare land value with respect to *T* requires the optimality condition (Eq. 4)

$$\frac{B'(T)}{B(T) - c} = \frac{r}{1 - e^{-rt}} . \qquad (4)$$

Hartman (1976) modified the Faustmann (1849) formula to a joint production problem. The Hartman (1976) model can be used to solve multifunctional forest management problems if the external benefits of the forest can be treated as an addition to the timber value. Assuming that the externality value is proportional to the timber value *B(t),* Hartman

(1976) formulated the present value of externality value $Q(T)$ for a single rotation as follows (Eq. 5):

$$Q(T) = \beta \int_0^T e^{-rt} B(t)dt \,, \qquad (5)$$

where β is the proportion of the timber value. The discounted perpetual value of the externality PV_{ext} (Eq. 6) is then

$$PV_{ext} = \frac{Q(T)}{1-e^{-rt}} \,, \qquad (6)$$

and the optimality condition of the maximization of externality value (Eq. 7) is

$$\frac{Q'(T)}{Q(T)} = \frac{re^{-rt}}{1-e^{-rt}} \,. \qquad (7)$$

Combining Equations 3 and 6, the present value of the joint production problem (PV_{tot}) is

$$PV_{tot} = PV_{timber} + PV_{ext} \,. \qquad (8)$$

Maximization of the joint production problem (Eq. 8) yields that the optimal rotation period between the optimal rotation of timber production T_{timber} and the optimal rotation of externality T_{ext} will be intermediate (Clark 1990).

Clark (1976) included thinnings in a general model of forest growth. In Clark's formulation, the general model of the dynamic of forest growth is based on the growth function $f(V)$ and the age factor $g(t)$, which is a positive, decreasing function of t,

$$\frac{dV}{dt} = g(t)\, f(V) \,,\ V(t_0) = V_0 \,, \qquad (9)$$

where t_0 denotes the initial age. Adding thinning removals $h(t)$ as the control variable in the general model, the dynamic of forest growth (Eq. 9) can be modified as (Eq. 10) follows:

$$\frac{dV}{dt} = g(t)\, f(V) - h(t) \,,\ t \ge t_0 \,,\ h(t) \ge 0 \,,\ V(t_0) = V_0 \,. \qquad (10)$$

The objective function of a single rotation problem is

$$PV = \int_{t_0}^{\infty} e^{-rt} \left[p - c(V) \right] h(t) dt \,, \qquad (11)$$

where p denotes price. The maximization of Equation 11 yields the optimality condition of optimal thinning and optimal rotation (Eq. 12),

$$r = \frac{\partial}{\partial V}\left[g(t)\, f(V)\right]. \qquad (12)$$

The optimization problems solved in this dissertation are more sophisticated than the theoretical models, because of the more complicated description of stand growth. Nevertheless, the preceding theoretical models provide the basis for stand management optimization.

2.2 Optimization methods applied to stand management

Numerous optimization studies on forest management have been published since the 1960s. In general, optimization methods can be classified into gradient methods and derivative free methods (Roise 1986, Eriksson 1994). The choice of a robust and accurate optimization algorithm depends on the convexity of the objective function and the dimensionality of variables. Previous studies concerning optimal stand management focus on applying new optimization methods to timber production. Brodie and Haight (1985), Valsta (1993), and Hyytiäinen (2004) have supplied recent and current syntheses across optimization methods and tree growth models.

Dynamic programming (DP) was the first optimization method to be applied to stand management optimization (e.g., Amidon and Akin 1968, Risvand 1969, Kilkki and Väisänen 1969, Brodie et al. 1978, Arthaud and Klemperer 1988, Valsta 1990, Gong et al. 2005). The disadvantage of DP in stand management optimization is its dimensionality problem. In other words, DP is efficient when the state space is defined by a small number of variables (Valsta 1993). Roise (1986) compared DP with three nonlinear programming (NLP) methods -- the method of Nelder and Mead (1965), Hooke and Jeeves' (HJ) direct search (Hooke and Jeeve 1961), and Powell's method (Powell 1964) -- using a Douglas fir whole-stand simulator. The efficiency of the algorithms was measured according to CPU (central processing unit) processing time and the convergence of an objective function value for soil expectation. The three NLP methods require multiple starting points in search of maximum local optima if a non-convex objective function appears. Valsta (1990) compared DP, random search, and HJ using a mixed pine-birch whole-stand growth model. The forward recursion version of DP was applied with five-year time intervals and three state variables: stand volume, birch percentage, and the number of trees. For random search and HJ, the decision variables are time between cuts, the proportions of total volume and birch volume removed, and the initial birch proportion. Stand age at breast height, stand volume, and the birch percentage of volume are state variables. Valsta's results show that the CPU processing time for DP was about ten times that of the other two methods. Both of their comparisons show that the HJ method is superior to other ones.

The HJ method has been widely applied in stand management optimization (e.g., Roise 1986, Haight and Monserud 1990, Valsta 1992a,b, Miina 1996, Thorsen and Helles 1998, Pukkala et al. 1998, Zhou 1998, Vettenranta and Miina 1999, Möykkynen et al. 2000, Cao 2003, Hyytiäinen et al. 2004, Pukkala and Miina 2005, Hyytiäinen et al. 2006, Pukkala 2009). However, Wikström and Eriksson (2000) suggested the Tabu search method (Glover 1989) as an alternative to the HJ method. Their optimization problem was considered a hierarchy of two problems. The first problem determines the time periods of cuts using a DROP/ADD heuristic guided by the Tabu search method. The second problem determines the removals of trees during these time periods as a sub-problem of the first problem. Wikström (2001) showed that the Tabu search method is also efficient at determining harvest periods for the even-aged problems. Pukkala (2009) recently introduced a new type of method referred to as a population-based or evolutionary computation method for stand management optimization. He compared three population-based optimization methods – differential evolution (Storn and Price 1997), particle swarm optimization (Kennedy and Eberhart 1995), and evolution strategy (Bayer and Schwefel 2002) -- as well as the method of Nelder and Mead (1965) to the HJ method. The results of Pukkla's study agreed with those of previous studies by Roise (1986) and Valsta (1990) in that the HJ method is suitable for maximizing or minimizing functions that are non-smooth and non-differentiable.

2.3 Timber production applications

The traditional optimization problems in forest management have been optimal thinning and the length of rotation. Optimal frequency, timing and the intensity of thinnings were first studied using a DP based on diameter-free whole-stand models with two or three state variables (e.g., Amidon and Akin 1968, Kilkki and Väisänen 1969, Brodie et al. 1978, Brodie and Kao 1979). More than three state variables have been used with DP based on a diameter-class whole-stand model (e.g., Riitters et al. 1982) and an individual-tree model (e.g., Haight et al. 1985). Using diameter-class whole-stand or individual-tree models, optimal thinning types have been determined for conifer cultures (e.g., Haight et al. 1985, Haight 1987, Arthaud and Klemperer 1988, Haight and Monserud 1990, Solberg and Haight 1991, Valsta 1992a,b, Eriksson 1994, Pelkki 1997, Pukkala et al. 1998, Pukkala and Miina 1998, Vettenranta and Miina 1999) and broad-leaved species (e.g., Pelkki 1998, 1999, Rautiainen et al. 2000). The decision variables for thinning type can be defined either by grouping diameter classes (e.g., Haight and Monserud 1990) or by linearly interpolating thinning parameters to other tree sizes with a small number of tree diameters (e.g., Valsta 1992b).

Other silvicultural activities, such as regeneration methods, planting density, precommercial thinning, and fertilization, have also been investigated. Kao (1979) optimized the intensity of precommerical thinning and fertilization for Douglas fir based on a diameter-free whole-stand model. Kao's model included two state variables (age and number of trees) for the precommercial thinning decision. An additional variable (basal area) was added for subsequent commercial thinning decisions. With the same state descriptors used in Kao's precommercial thinning study, Kao (1979) handled the fertilization decision through the computations to three levels of fertilization (0, 200, and 400 lbs/acre) with no expansion of state space. Solberg and Haight (1991) applied a stage-structured model and added the determination of optimal planting density for Norway spruce stands. Their thinning problem was formulated as a discrete-time optimal-control problem. Thinning type, thinning intensity, and timing of thinning were determined simultaneously with planting density and rotation length. Zhou (1998) studied the economic optimization of natural regeneration for Scots pine based on a diameter-free whole-stand model. His model simultaneously determined the optimal harvesting time of the initial stand, the number of seed trees, the length of the seed tree period, the stand density after precommercial thinning, the timing and intensities of commercial thinnings and rotation length. Zhou (1998) set the dominant heights to 6 m and 11 m, the heights at which precommercial thinning and the first commercial thinning should be carried out. His estimation of the timing of precommercial thinning and the first commercial thinning was based on Vuokila (1982) and Hägglund (1974). Hyytiäinen et al. (2006) analyzed the economic returns of regeneration methods that use a process-based Scots pine model. They investigated four alternative stand establishment methods (planting, sowing, and natural regeneration with 25 and 100 seed trees ha^{-1}) and three soil preparation intensities (unprepared, conventional harrowing, intensive harrowing). In contrast to Zhou (1998), the time interval between regeneration harvest and removal of seed trees was set to ten years after the regeneration harvest in Hyytiäinen et al. (2006). At the same time, precommercial thinning was assumed to have taken place with a target residual density of 2000 trees ha^{-1}.

The timber production of mixed-species stands has been investigated based on whole-stand (e.g., Valsta 1986) and individual-tree models (e.g., Haight and Monserud 1990, Pukkala et. al 1998, Vettenranta and Miina 1999). Valsta (1986) optimized species composition in even-aged pine-birch stands by defining thinnings as changes in stand volume and birch percentage. Haight and Monserud (1990) presented an any-aged management formulation for mixed-conifer stands in the Northern Rocky Mountains. For the purpose of improving convergence, they set planting and site preparation schedules, and grouped diameter classes and species. Similar to the groupings of diameter in Haight and Monserud (1990), Pukkala et al. (1998) and Vettenranta and Miina (1999) divided the diameter distribution of each species into three classes (small, medium, and large) for Scots pine and Norway spruce mixtures.

The effects of butt rot (Möykkynen and Miina 2002, Cao 2003) and juvenile growth (Hyytiäinen et al. 2005) on timber quality have been taken into account in timber production based on empirical models. Integrating a process-based growth model for Scots pine into economic optimization, Hyytiäinen et al. (2004) reported economic optimization results for timber production using timber grade prices (top log, middle log, butt log, and pulpwood). Their bucking system has also been applied to optimizing stand establishment based on the same process model (Hyytiäinent et al. 2006).

2.4 Non-timber production applications

Previous studies about non-timber production concentrate on theoretical analysis. Since the 1980s, interest in the use of multi-criteria decision models (MCDM) in forest management applications has grown (Pukkala 2002, Kangas et al. 2008). MCDM methods have been employed in non-timber production such as amenity, biodiversity, carbon sequestration, and recreation (e.g., Chang and Buongiorno 1981, Mendoza et al. 1987, Buongiorno et al. 1994, Wikström and Eriksson 2000). On the other hand, the Hartman (1976) model has been used extensively to solve joint production problems such as timber production and amenity (e.g., Koskela and Ollikainen 2001, Uusivuori and Kuuluvainen 2008), timber production and biodiversity (e.g., Koskela et al. 2007a,b), and timber production and carbon sequestration (e.g., van Kooten et al. 1995, Gong and Kriström 1999, Pohjola and Valsta 2007).

The importance of carbon sinks in global warming creates potential outputs for the economic value of forests in addition to timber production; these outputs include forest bioenergy production and carbon sequestration. Previous studies have reported on the relationship between rotation and decision-making criteria concerning timber production and carbon sequestration based on relative simple tree growth models (e.g., van Kooten et al. 1995, Romero et al. 1998, Huang and Kronrad 2001). That is, the optimal rotation that maximizes the joint timber and carbon sequestration is longer than the Faustmann rotation, but shorter than the MSY (maximum sustainable yield) rotation. Carbon cost-effectiveness studies concentrate on the effects of financial incentives (e.g., Hoen and Solberg 1994, van Kooten et al. 1995, Huang and Kronrad 2001, Backéus et al. 2006, Pohjola and Valsta 2007). van Kooten et al. (1995) and Backéus et al. (2006) pointed out that a high carbon price may cease harvesting. In addition, van Kooten et al. (1995) reported that a decrease in the carbon emission rate shortened the optimal rotation. Most previous studies simplified the optimal rotation problem as a non-thinned management regime, and assessed forest carbon only for stem volume. Pohjola and Valsta (2007) applied biomass expansion factors (BEFs), which convert stem volume to aboveground biomass for Scots pine and Norwary spruce stands. In contrast to van Kooten et al. (1995), Pohjola and Valsta (2007) used a 100% carbon emission rate, which assumes forest carbon is emitted into the atmosphere immediately after harvesting.

Although the issues raised by forest bioenergy development have received attention in recent years, optimization studies investigating forest bioenergy and stand management are still lacking. Kärkkäinen et al. (2008) recently reported the recovery of energy wood in different cutting and climate scenarios in Finland, but their results were based on a linear programming approach (Lappi 1992) which selected the optimum combination of management regimes from a predefined set of alternatives.

3 MATERIAL AND METHODS

3.1 Forest models

3.1.1 Stand growth simulators

The even-aged stand projection models used in this dissertation include distance-independent individual-tree empirical (**I**) and process (**II**) Norway spruce models, as well as distance-independent individual-tree process (**III, IV**) Scots pine models. In Study **I**, we updated the empirical growth models used in the MELA system (Siitonen et al. 1996) based on Hynynen et al. (2002). Their individual-tree growth equations are based on data collected from permanent sample plot data sets and statistics of the 7th and the 8th Finnish National Forest Inventory. Tree growth was predicted using models for tree basal area growth (measured at breast height), tree height growth, and crown ratio development. The basal area growth of an individual tree (i_{ba}) was predicted as a function of tree variables (tree diameter at breast height, d, crown ratio, cr, and mean height of the dominant trees, H_{dom}), site variables (site index, SI, fertility class, and total annual temperature sum, TS), and variables describing stand density (RDF) and the relative density of trees larger than the subject tree ($RDFL$). The relative density factor, RDF, is the ratio between the actual stand density and the density of a stand undergoing self-thinning (Hynynen et al. 2002, p.30-31). Mortality resulting from competition was determined using the site-dependent self-thinning model of Hynynen et al. (2002, p.53-54).

The process-based PipeQual simulator (Mäkelä 1997, 2002, Mäkelä and Mäkinen 2003, Kantola et al. 2007) is based on the pipe model theory (Shinozaki et al. 1964) and the theory of crown allometry (Mäkelä and Sievänen 1992). In Study **II**, stand growth was simulated based on the PipeQual Norway spruce version (Kantola et al. 2007), which was modified and parameterized from the Scots pine version (Mäkelä 1997, 2002, Mäkelä and Mäkinen 2003). Model parameters for Study **II** are based on a Finnish thinning experiment located in Heinola and a Swedish nutrient addition experiment located in Flakaliden. In the studies (**III** and **IV**) on Scots pine, we incorporated the PipeQual Scots pine version (Mäkelä 1997, 2002, Mäkelä and Mäkinen 2003) with stand management optimization. The PipeQual Scots pine version is parameterized for pure stands of Scots pine growing in Fennoscandia.

The PipeQual model applies a hierarchical approach, which consists of STAND, TREE, WHORL, and BRANCH modules. At the branch level, the branch module provides the annual dynamics of individual branches and their properties in each whorl. At the whorl level, the whorl module describes the vertical structure of stem and branches. At the tree level, tree structure is composed of foliage, fine roots, stem, branches, and transport roots. Annual tree growth is calculated from tree photosynthesis and respiration. The modules of the process-based growth model are interconnected through parametric inputs and outputs at a time resolution of one year (Kantola et al. 2007). A more explicit description of the PipeQual model as a dynamic system for stand management optimization appears in Hyytiäinen et al. (2004).

One advantage of the process model over empirical models is its detailed description of crown morphology and stem taper in the prediction of wood quality. A benefit of using the PipeQual simulator is that this system enables the detailed description of the 3D stem structure of logs and biomass production in different tree compartments. Hyytiäinen et al. (2004) compared the empirical (Hynynen et al. 2002) and the process-based (Mäkelä 1997, 2002, Mäkelä and Mäkinen 2003) models using the same initial stand data and definition of thinning for a young Scots pine stand. Their results show that both models are logical, but somewhat different in optimal thinning regimes and stand development. They explained that these differences stemmed from distinct specifications of tree mortality.

3.1.2 Models for predicting wood quality

In Study **II**, we applied empirical models developed by Mäkinen et al. (2007) for predicting wood and tracheid properties based on variables such as annual ring width, number of rings, and distance from the pith. Wood density, tracheid length, and tracheid width were also related to site index H100 (dominant height at age 100). The dimensions and branch properties of sawlogs are the most import factors affecting log grading. In Study **II**, we developed a log grading system for Norway spruce, which was modified from the Scots pine log grading system of Hyytiäinen et al. (2004). Butt logs, middle logs, and top logs were graded according to branch size, crown base length, and top diameter of the sawlogs. Because of various quality defects, a logistic regression model for log downgrading into pulpwood based on tree age and diameter at breast height (Mehtätalo 2002) was included for log grading calculations.

Study **III** employed multinomial logistic regression models for predicting yields of lumber grades and by-products of individual Scots pine trees developed by Lyhykäinen et al. (2009). Their sawn wood grading models use stem and crown dimensions as explanatory variables. The proportion of sawn wood grades is a function of the height of the crown, the height of the lowest dry branch, tree diameter at breast height, and stem volume. The end products of Scots pine include center (grades A, B, C, and D) and side (grades A, B, C, and D) sawn timber (Nordic timber-grading rules 1994), chips, bark, sawdust, and pulpwood.

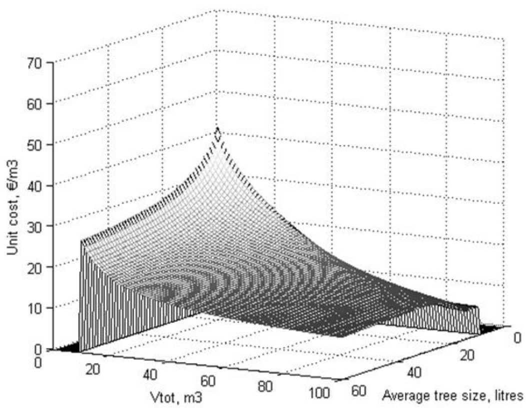

Figure 1. Unit costs of energy wood harvesting from early thinnings.

3.1.3 Timber and energy wood logging models

In Study **III**, the productivity of mechanized cutting for energy wood production from early thinnings (Figure 1) is based on a time consumption model for a thinning harvester equipped with an accumulating felling head (Laitila et al. 2004). Laitila (2008) reported that such a two-machine (harvester-forwarder) system is currently the most cost competitive logging system in precommercial thinning in Finnish conditions.

Through all four studies (**I**, **II**, **III**, and **IV)**, we employed the logging cost model of Kuitto et al. (1994), which is based on time consumption equations for mechanized cutting and forest haulage specifications. Total logging costs consist of fixed costs, felling costs and haulage costs. The logging cost is a function of harvested volume, productivity of felling (time spent on shifting and handling), and productivity of on-site transport (time spend on loading, delays, hauling loads, driving without a load, and unloading) for sawlogs and pulpwood, respectively.

3.1.4 Carbon assessment models

In Study **IV**, we compared three carbon assessment methods. Carbon assessment method I (CI) calculates stem wood carbon only. A dry weight density of 0.39 t m^{-3} and a carbon fraction of 0.512 were used in CI (Karjalainen et al. 1994). Carbon assessment method II (CII) employs biomass expansion factors (BEFs) developed by Lehtonen et al. (2004), who applied volume and biomass equations to describe the allometry of single trees. The stand-level, age-dependent BEFs convert stem volume directly to the dry weight of biomass components for stem, foliage, branches, dry branches, bark, stump, coarse roots and fine roots (Lehtonen et al. 2004). Carbon assessment method III (CIII) is based on the process-based model (Mäkelä 1997, 2002, Mäkelä and Mäkinen 2003), which predicts biomass production for foliage, fine roots, stem sapwood, branch sapwood, coarse roots, stem heartwood, branch heartwood, and dry branches. The biomass was dry mass, and the carbon fraction was assumed to be 0.5 in both CII and CIII.

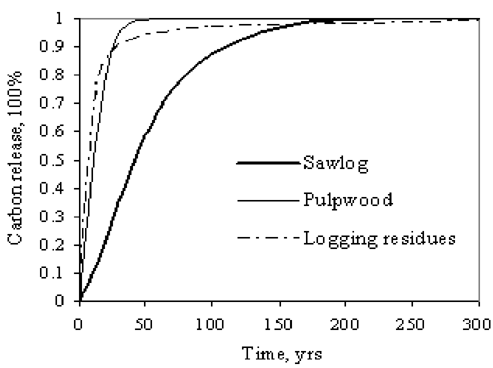

Figure 2. Carbon release as a function of time by timber assortments.

Models for predicting the carbon emission rates of sawlogs and pulpwood (Karjalainen et al. 1994) and the decomposition rate of logging residues (Liski et al. 2005) have been developed and widely applied (e.g., Hynynen et al. 2005, Liski et al. 2006, Pohjola and Valsta 2007, Palosuo et al. 2008). In Study **IV**, the carbon emission rates over time for sawlogs and pulpwood were based on Karjalainen et al. (1994), and the decomposition rate of logging residues over time was based on Liski et al. (2005) and Palosuo et al. (2008) (Figure 2).

3.2 Nonlinear programming algorithms

3.2.1 The Hooke and Jeeves direct search method

Individual-tree stand growth simulators are complicated simulation systems consisting of several sub-models such as diameter increment, height increment, mortality, and stem taper. The complexity of individual-tree models leads to multidimensional nonlinear optimization problems. Nonlinear programming is a class of optimization problems in which either the objective function is nonlinear or the constraint set is specified by nonlinear equations and inequalities. In contrast to discrete problems, nonlinear programming lies within the continuous category (Bertsekas 1999). Nonlinear programming algorithms, such as multidimensional search methods without the use of derivatives (Bazaraa et al. 1993, Bertsekas 1999), are useful tools for solving non-smooth and non-differentiable optimization problems for individual-tree stand growth models. The basic method in this category is called the cyclic coordinate method. More efficient multidimensional search methods include the Hooke and Jeeves direct search method (Hooke and Jeeves 1961), the method of Rosenbrock (1960), and the method of Nelder and Mead (1965).

The method of Hooke and Jeeves (HJ) begins with an exploratory search. Given x_1, an exploratory search along the coordinate directions produces point x_2. A pattern search along the direction $x_2 – x_1$ then leads to point y. Another exploratory search starting from y gives point x_3. The next pattern search takes place along the direction $x_3 – x_2$, yielding y'. The process is then repeated (Bazaraa et al. 1993). There are two types of the HJ method: the HJ method that uses line search and the HJ method with discrete steps. The algorithm of the HJ method that uses line search begins with a scalar $\varepsilon > 0$ chosen to serve in terminating the algorithm. Choose a starting point x_1, let $y_1 = x_1$, let k = j = 1, and then go to step 1: Let λ_j be an optimal solution to the problem of minimizing $f(y_j + \lambda d_j)$ subject to λ in R^1, and let $y_j + 1 = y_j + \lambda_j d_j$. If j < n, replace j with j + 1, and repeat step 1. Otherwise, if j = n, let $x_k + 1 = y_n + 1$. If $\|x_{k+1} – x_k\| < \varepsilon$, stop; otherwise, go to step 2: Let $d = x_{k+1} – x_k$, and let λ^* be an optimal solution to the problem of minimizing $f(x_{k+1} + \lambda d)$ s.t. λ in R^1. Let $y_1 = x_{k+1} + \lambda^* d$, let j = 1, replace k with k + 1, and repeat step 1 (Bazaraa et al. 1993).

The HJ method was originally proposed with discrete steps rather than line searches as described above (Bazaraa et al. 1993). The algorithm of the HJ method with discrete steps begins with the initialization step: Let $\mathbf{d}_1,...,\mathbf{d}_n$ be the coordinate directions. Then choose three parameters: a scalar $\varepsilon > 0$ to serve in terminating the algorithm, an initial step size, $\Delta \geq \varepsilon$, and an acceleration factor, $\alpha > 0$. Choose a starting point x_1, let $y_1 = x_1$, let k = j = 1, and then go to step 1: If $f(y_j+\Delta d_j) < f(y_j)$, let $y_{j+1} = y_j + \Delta d_j$. Otherwise, if $f(y_j-\Delta d_j) < f(y_j)$, let $y_{j+1} = y_j - \Delta d_j$; if not, let $y_{j+1} = y_j$. Then go to step 2: If j < n, replace j with j + 1, and repeat step 1. Otherwise, if $f(y_{n+1}) < f(x_k)$, go to step 3; if not, go to step 4. Step 3 is a pattern search: Let $x_{k+1} = y_{n+1}$, and let $y_1 = x_{k+1} + \alpha(x_{k+1} - x_k)$. Replace k with k+1, let j = 1, and go to step 1. The step size is reduced in step 4: If $\Delta < \varepsilon$, stop. Otherwise, replace Δ with $\Delta/2$. Let $y_1 = x_k$, $x_{k+1} = x_k$, replace k with k + 1, let j = 1, and repeat step 1 (Pukkala 2009).

3.2.2 An optimization model in the stand management tool SMA

In Study **I**, we employed an optimization method similar to a deterministic version applied by Valsta (1992b). The basic approach is after that of Kao and Brodie (1980) and Roise (1986). The stand growth simulator reflects the fact that the optimization algorithm knows of the simulator only by the objective function values it obtains in return for decision variable vectors. The vector of decision variables consists of times between forest operations and information on how the operation is executed (e.g., thinning percentages at different tree diameters) or the number of trees per hectare.

The optimization algorithm is based on the HJ method, which has proved successful in solving complex non-differentiable forestry problems (e.g., Haight and Monserud 1990, Valsta 1992b). The modifications to the original algorithm (HJ with discrete steps) are based on Osyczka (1984), and are explained in detail by Valsta (1992b). The number of control variables nx in the problem of optimizing thinnings and rotation is given by $nx = n(m + 1) + 1$, where n denotes the number of thinnings, and m denotes the number of thinning-type variables (Valsta 1992b). The applied solution procedure does not explicitly utilize the dynamic structure of the problem. This procedure appears to be potentially inefficient (solving a dynamic problem without recognizing the dynamics involved), but because of the complex nature of individual-tree based stand dynamics, it has proved to be a more successful approach than dynamic programming (Valsta 1993).

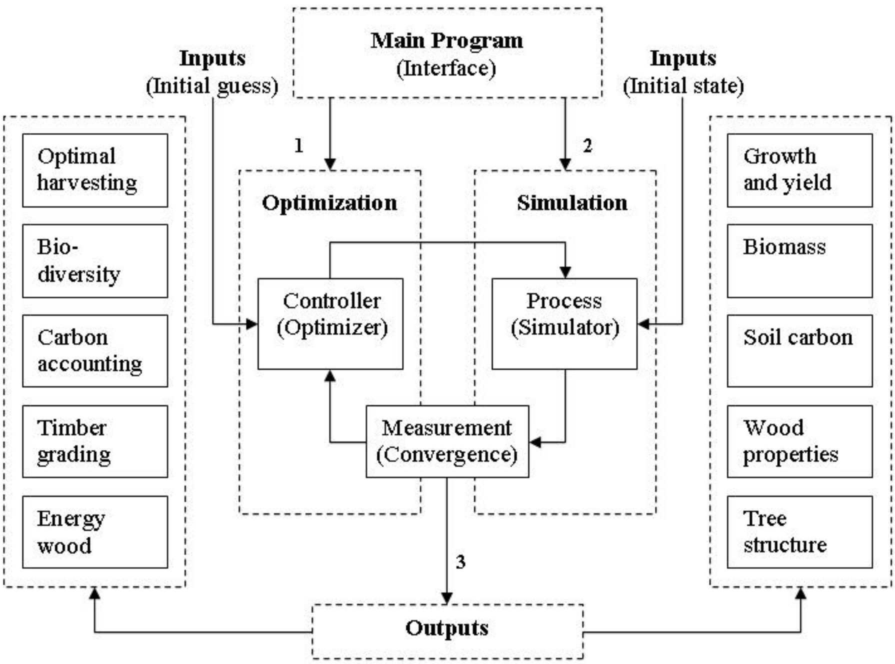

Figure 3. Flowchart of OptiFor.

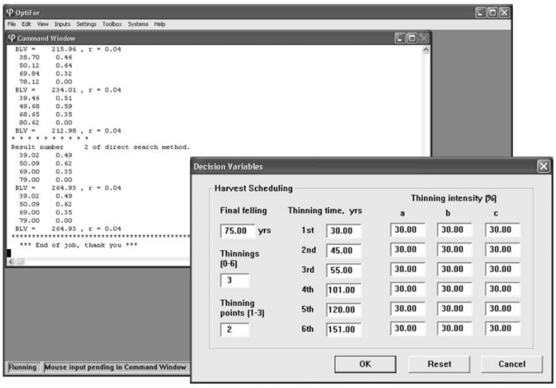

Figure 4. The input and output interface of the OptiFor computer program.

3.3 Development of the OptiFor simulation-optimization system

3.3.1 OptiFor structure

The OptiFor simulation-optimization system consists of ecological and optimization models (Figure 3). In Study **II**, we linked models for predicting wood and tracheid properties (Mäkinen et al. 2007), and timber grading with the process-based growth model PipeQual (Mäkelä 1997, 2002, Mäkelä and Mäkinen 2003, Kantola et al. 2007) for Norway spruce. In Study **III**, models for financial return (Faustmann 1849), logging cost (Kuitto et al. 1994, Laitila et al. 2004), and sawn wood grading (Lyhykäinen et al. 2009) were combined with the PipeQual Scots pine simulator and optimization algorithms (Hooke and Jeeves 1961, Osyczka 1984). In Study **IV**, we integrated carbon assessment models (Karjalainen et al. 1994, Lehtonen et al. 2004, Palosuo et al. 2008) into the OptiFor simulation-optimization system developed in Study **III**. As Figure 3 shows, the optimizer serves as the controller, and the simulator as a process.

In Study **III**, we developed the OptiFor computer program interface (Figure 4). The dialogue-based windows interface is friendly and suitable for the requirements of inputs and outputs in simulation-optimization calculations. The OptiFor simulation-optimization system was developed with FORTRAN programming.

The OptiFor simulation-optimization system employs Osyczka's direct and random search algorithm (Osyczka 1984), which is a combination of random search and Hooke and Jeeves' direct search (Hooke and Jeeves 1961). Osyczka's algorithm improves direct search solutions by inserting neighborhood search and shotgun search iterations between direct search runs. The first step goes to Hooke and Jeeves' direct search. The second step, neighborhood search, attempts to find a better solution around the direct search result to avoid premature convergence. The third step, shotgun search, provides a new starting point for a new direct search phase. Figure 5 shows the default algorithm parameters of Osycaka's direct and random search. One may change the default values to improve the accuracy of the optimization solutions, but the calculations will require more time.

The optimal thinning regime is formulated as a bound-constrained optimization problem (Eqs. 13-15):

$$\max \quad f(\mathbf{u}, \mathbf{H} : \mathbf{x}(t_0)), \tag{13}$$
$$\text{s.t.} \quad \mathbf{u} = (u_1, \ldots, u_{n+1}), u_i \in [1, 25], \tag{14}$$
$$\mathbf{H} = (h_{ij})_{n \times m}, h_{ij} \in [0, 1]. \tag{15}$$

We use control variables to solve the dynamic problem of stand management as static optimization. In this formulation, no state variables **x**(t) (tree diameter, height, etc.) are used in the optimization algorithm. Rather, the state variable values are computed inside the stand simulator, given the initial state $\mathbf{x}(t_0)$. The bare land value (BLV) of a stand is maximized by changing the set of control variables **u** (time between the *i*-1th and the *i*th thinnings, yrs) and **H** (thinning rate h_{ij} in the *j*th tree-size class at the *i*th thinning), where $f : R^n \times R^m \to R$ is the objective function for the BLV of a thinning regime, R^m denotes *m*-dimensional (R^n , *n*-dimensional) real Euclidean space. The BLV of a thinning regime for timber production (**I**, **III**, and **IV**) can be expressed as follows (Eq. 16):

$$\text{BLV} = \frac{\sum_{i=1}^{n+1} \left[\sum_{j=1}^{m} \sum_{k=1}^{l} p_k v_{ijk} - c_i \right] e^{-rt_i} - c_0}{1 - e^{-rt_{n+1}}}, \tag{16}$$

where *n* is the number of thinnings, *n* + 1 refers to the final felling, c_0 is the discounted stand establishment cost, and *l* denotes timber categories. The thinning type can be defined with one or more thinning variables. For example, one thinning variable indicates row thinning; two thinning variables denotes the selection of thinning rates in the first and the last tree size classes; three thinning variables reflects the selection of thinning rates in the first, middle, and last tree-size classes. The decision variables of the thinning type are then defined by linearly interpolating the thinning rate h_{ij} in the *j*th tree-size class to other tree sizes.

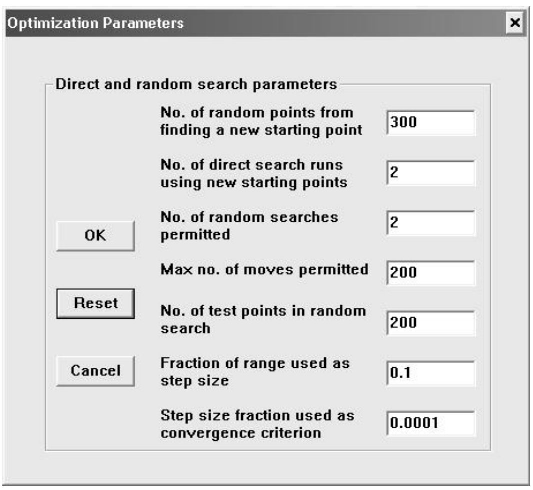

Figure 5. Parameters of Osyczka's direct and random search algorithm.

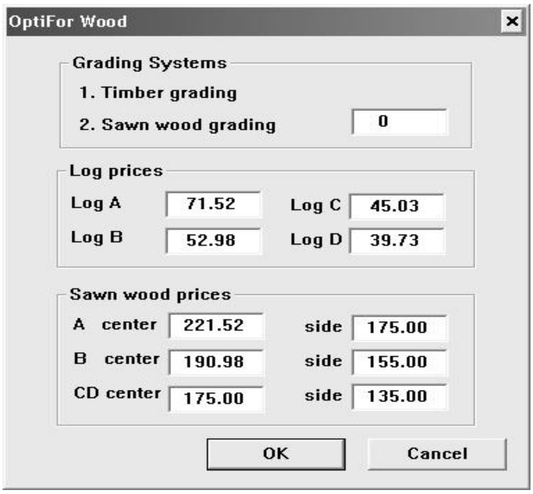

Figure 6. The dialogue window of OptiFor Wood.

3.3.2 OptiFor Wood

Two grading systems are linked to the PipeQual simulator in OptiFor (Figure 6). The log grading system developed in Study **II** was first connected to the PipeQual Norway spruce version. The effects of thinning and fertilization on log grading can be studied with a scenario approach. The net present value (NPV_S) of existing stock based on alternative silvicultural treatments (**II**) can be computed as follows (Eq. 17):

$$\mathrm{NPV_S} = \sum_{i=1}^{n+1}\left[\sum_{j=1}^{m}\sum_{k=1}^{l} p_k v_{ijk} - c_i\right] e^{-r(t_i - t_0)}\,, \tag{17}$$

where t_0 denotes initial stand age, l denotes timer categories by wood quality (butt log, middle log, top log, pulpwood based on tracheid length, and wood density).

In addition, the sawn wood grading model (Lyhykäinen et al. 2009) was connected to the PipeQual Scots pine version in Study **III**. The effects of optimal thinning and energy wood harvesting on sawn wood grading can be analyzed by optimizing the joint production of timber and energy wood (**III**).

3.3.3 OptiFor Bioenergy

The logging cost model for energy wood from young stands by Laitila et al. (2004) was linked to the OptiFor simulation-optimization system in Study **III**. The economic viability of harvesting energy wood from young stands can be evaluated using three decision criteria: profitable, compulsory, and flexible energy wood harvesting (Figure 7).

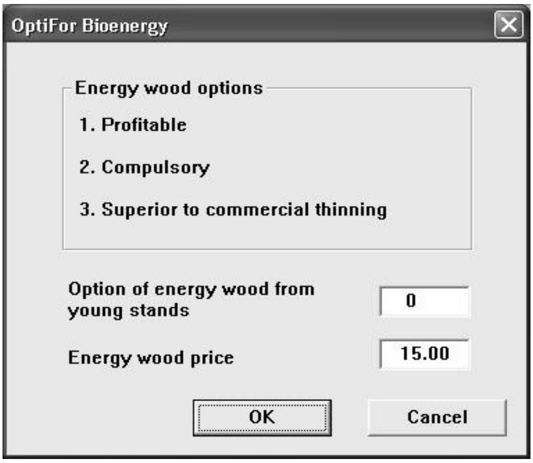

Figure 7. The dialogue window of OptiFor Bioenergy.

If the first thinning is conducted as energy wood harvesting, conventional logging will be applied from the second thinning. Rather, the energy wood logging cost (c_E) and income will be computed for the first thinning (Eq. 18). The objective function of BLV (Eq. 16) will be modified (**III**) by adding the net present value of energy wood (NPV_E), where p_E denotes the energy wood price.

$$\mathrm{NPV_E} = \left[\sum_{j=1}^{m} p_E v_{1j} - c_E \right] e^{-rt_1} . \qquad (18)$$

3.3.4 OptiFor Carbon

In Study **IV,** we developed the simulation-optimization tool OptiFor Carbon for optimizing timber production and carbon sequestration. Models for predicting biomass expansion factors (Lehtonen et al. 2004) and the carbon emission rates of wood products (Karjalainen et al. 1994) and logging residues (Palosuo et al. 2008) were integrated into the OptiFor simulation-optimization system in Study **IV**. A selection of carbon assessment methods is available for optimizing timber production and carbon sequestration (Figure 8).

The joint production model for timber production and carbon sequestration used in OptiFor Carbon is based on Pohjola and Valsta (2007). The objective function of the joint production problem (Hartman 1976) was modified from the Faustmann (1849) formula. The total returns from forest management comprise the net present value of timber (NPV_T) and the net present value of carbon (NPV_C),

$$\mathrm{NPV_C} = \sum_{t=0}^{t_{n+1}} cs_t \cdot e^{-rt} - \sum_{i=1}^{n+1} et_i \cdot e^{-rt_i} , \qquad (19)$$

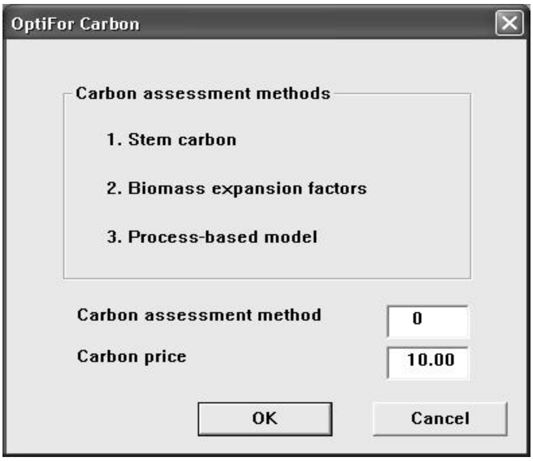

Figure 8. The dialogue window of OptiFor Carbon.

where the increment of carbon stock is subsidized annually (*cs* denotes carbon subsidy), and carbon emissions are taxed when timber is harvested (*et* denotes carbon emission tax). Embedding Equation 19 into Equation 16, the objective function of BLV then becomes the joint production problem of timber production and carbon sequestration (**IV**).

3.4 Biological and economic data

The initial stand states of Norway spruce (Table 1) were described using inventory information from well-stocked stands (**I**), a Finnish thinning experiment at ten years with an initial density of 3000 trees ha^{-1} (**II**) located in Heinola, and a Swedish nutrient addition experiment at seven years with an initial density of 2500 trees ha^{-1} (**II**) located in Flakaliden. The initial states of 15 example Scots pine stands (Table 2) and pure Scots pine stands (**III** and **IV**) were well established. The diameter distributions were derived artificially based on site type, temperature sum, and initial stand density.

The interest rates, roadside prices, and costs throughout four studies are expressed in real terms. A 3% interest rate was constantly used for all four studies. The roadside prices of Norway spruce (**I**) came from Hyytiäinen and Tahvonen (2002). The price ratios between Norway spruce sawlog categories (**II**) were based on Kivinen (2004). The roadside prices of Scots pine (**III** and **IV**) were the same as those in Hyytiäinen et al. (2004). The roadside price of Scots pine energy wood – including government subsidies – was assumed to be €15 m^{-3} (**III**), and the presumed carbon price was €40 t^{-1} (**IV**). Sensitivity analyses of prices and interest rates were conducted in all studies but Study **III**.

The unit silvicultural costs assumed for Norway spruce stands (**I**) were €160 ha^{-1}, €202 ha^{-1}, €350 ha^{-1}, and €160 ha^{-1} for soil preparation, planting, seedling and tending, respectively. The unit silvicultural costs assumed for Scots pine stands (**III** and **IV**) were €142 ha^{-1}, €600 ha^{-1}, and €276 ha^{-1} for soil preparation, sowing, and tending, respectively. The fixed cost of logging was €100 ha-1 (**I-IV**), and hourly costs were 61.3 h^{-1} (**I** and **II**) and €75.67 h^{-1} (**III** and **IV**) for the felling phase, and €47.1 h^{-1} (**I** and **II**) and €53.35 h^{-1} (**III** and **IV**) for the haulage phase.

Table 1. Initial stand states of 14 Norway spruce stands.

Stand	Age	#tree	BA	Hdom	H100	ST	Study
1	37	1375	12.0	13.0	25.7	MT	**I**
2	25	1400	20.5	11.7	29.2	MT	**I**
3	45	1475	31.6	14.5	24.3	OMT	**I**
4	38	1475	17.0	12.6	25.7	OMT	**I**
5	34	1700	26.5	15.9	30.7	MT	**I**
6	30	1700	26.3	10.9	24.6	OMT	**I**
7	33	1825	26.6	13.8	27.5	OMT	**I**
8	36	1825	29.3	14.5	26.7	OMT	**I**
9	48	1875	23.3	13.9	22.3	MT	**I**
10	36	2250	29.9	14.1	26.9	MT	**I**
11	42	2300	31.0	15.9	28.0	MT	**I**
12	36	2300	33.6	13.1	25.8	OMT	**I**
13	10	3000	0.0	1.3	34.3	OMT	**II**
14	7	2500	0.0	1.0	18.0	-	**II**

Table 2. Initial stand states of 15 Scots pine stands.

Stand	Age	#tree	BA	Hdom	H100	ST	TS	Study
1	29	1500	6.4	7.9	17.3	CT	1300	**III, IV**
2	29	2000	7.3	7.7	17.6	CT	1300	**III**
3	29	3000	9.1	7.4	17.5	CT	1300	**III**
4	23	1500	7.6	7.9	22.1	MT	1100	**III, IV**
5	23	2000	8.8	7.8	21.9	MT	1100	**III**
6	23	3000	11.2	7.4	21.5	MT	1100	**III**
7	20	1500	7.4	8.0	28.3	MT	1300	**III, IV**
8	20	2000	8.6	7.8	27.9	MT	1300	**III**
9	20	3000	10.8	7.5	27.3	MT	1300	**III**
10	27	1500	7.0	7.9	18.2	VT	1100	**III**
11	27	2000	8.2	7.7	18.4	VT	1100	**III**
12	27	3000	10.0	7.4	18.4	VT	1100	**III**
13	23	1500	7.0	7.9	25.7	VT	1300	**III, IV**
14	23	2000	8.1	7.8	25.4	VT	1300	**III, IV**
15	23	3000	10.0	7.5	24.8	VT	1300	**III, IV**

Note: Age is initial age (yrs), #tree denotes the number of trees per hectare, BA denotes basal area (m^2 ha^{-1}), Hdom denotes dominant height (m), H100 denotes dominant height (m) at age 100, ST denotes site type, CT = *Calluna* site, MT = *Myrtillus* site, VT = *Vaccinium* site, OMT = *Oxalis-Myrtillus* site, and TS denotes temperature sum (d.d.).

4 RESULTS

4.1 Effects of initial stand states on the optimal thinning and rotation of Picea abies stands (I)

One of the most important issues in stand management is thinning. In Study **I**, we analyzed the effects of young stand characteristics on optimal thinning regime and length of rotation periods for even-aged Norway spruce (*Picea abies* (L.) Karst.) stands. Stand development was based on distance-independent, individual-tree growth models (Hynynen et al. 2002). The young stand data were from 12 well-stocked Norway spruce stands in southern Finland. Owing to variations in management intensity and early stand development, the initial stand structures do not follow the optimal path starting from bare land. Optimal stand management is therefore determined separately for the first ongoing rotation and the later rotation periods initiated from bare land.

The results showed that optimal thinning regimes and rotation period depend on site quality and initial stand characteristics. The optimal number of thinnings during the rotation period was sensitive to the interest rate for sparse and moderate density stands, but less sensitive to that for denser stands. Raising the interest rate reduced rotation length and, subsequently, the optimal number of thinnings. At a 3% interest rate, the optimal number of thinnings was five or six for those stands that were initially at high density. Only two or three thinnings was optimal for stands with lower initial density.

The first thinning was optimally conducted after the majority of removed trees had reached commercial dimensions, but before the trees began to die from overcrowding. The timing of the first thinning was sensitive to initial density. Higher initial stand density typically led to earlier first thinning. Dense stands reached earlier the stage when self-thinning due to overcrowding began.

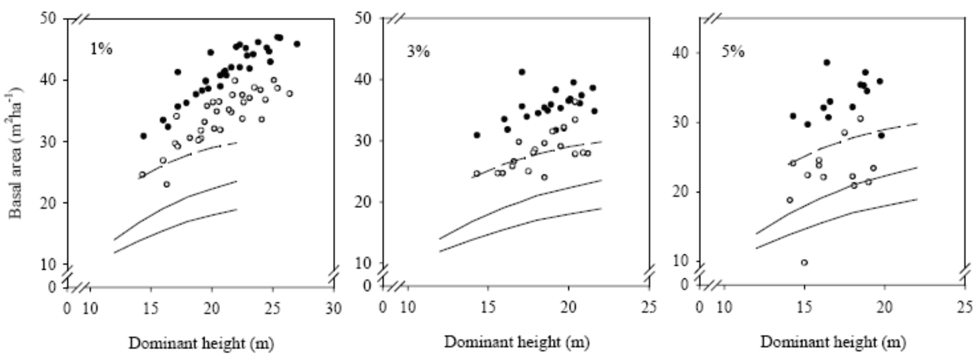

Figure 9. Basal area before (black) and after (white) thinnings as a function of dominant height at 1%, 3% and 5% interest rates in relation to recommended before-thinning level (broken line) and after-thinning range (solid lines) (Study **I**).

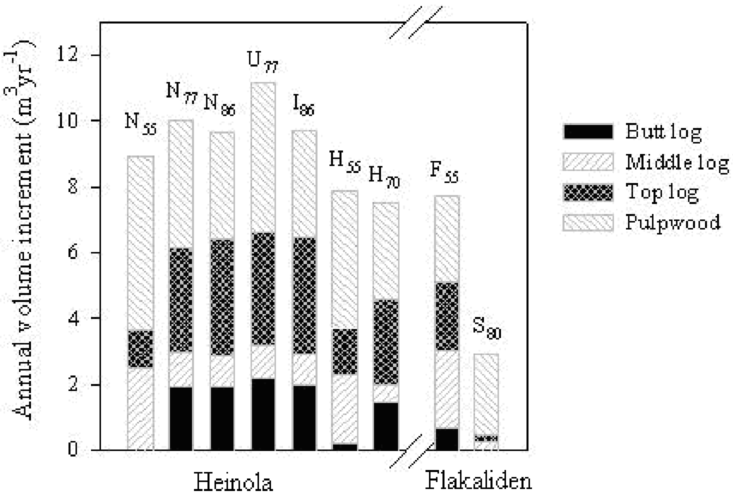

Figure 10. Annual volume increment over the rotation in Heinola and Flakaliden (Study **II**).

At the first thinning, the optimal thinning type depended on initial density. Thinning from both ends of the diameter distribution turned out to be optimal for initially dense stands. At the second and subsequent thinnings, thinning from above proved superior. At a low interest rate, thinning from below was optimal for the first thinning regardless of stocking level. For our data, optimal rotation periods varied from 61 to 92 years at a 3% interest rate. High variation in length of rotation period was due to the sensitivity to site quality, initial stand structure and stand density.

Our results show that the optimal stocking level was highly sensitive to the interest rate (Figure 9). At lower interest rates, light thinnings were attractive. There was less variation in basal areas before and after thinning (Figure 9), and the stocking level was higher than silvicultural recommendations (Tapio 2001) throughout the rotation period. At higher interest rates, the basal area after thinning varied more with their initial state.

4.2 Effects of silvicultural treatments on wood properties and economic returns for Norway spruce (II)

Knowledge of wood and tracheid properties such as wood density, latewood proportion, tracheid length and width, is crucial for the pulp and paper industries. In Study **II**, we conducted two case studies: case I compared different thinning intensities in Heinola, southeastern Finland, and case II considered the effects of nutrient addition in Flakaliden (before nutrition addition, H100 = 17-19 m), northern Sweden.

In Heinola, seven thinning alternatives (N_{55}, N_{77}, N_{86}, U_{77}, I_{86} H_{55}, H_{70}; subscript numbers denote rotation length, N normal thinning, U unthinned after the 1st commercial thinning, I slightly intensive, H heavy thinning) were simulated to study the effects of thinning intensity and frequency, as well as rotation length. Our results show that the regimes with longer rotation lengths resulted in higher values of the annual volume increment (Figure 10). Increasing the thinning intensity resulted in a lower mean wood density, tracheid length, and latewood proportion in harvested wood. Wood density and tracheid length of harvested pulpwood decreased slightly in later thinnings and final cuts at a higher thinning rate. Thinning regimes with high early growing stock and decreasing later growing stock were economically the most profitable.

In Flakaliden, annual forest nutrient addition was applied from the age of 23 years onwards. The growth and yield of two unthinned treatments, with (F) and without (S) nutrient addition, were compared to rotation lengths of 55 (F_{55}) and 80 (S_{80}) years, respectively. Nutrient addition significantly accelerated the tree growth rate and, consequently, decreased simulated wood density, latewood proportion, and tracheid length, but increased tracheid width. On the other hand, nutrient addition significantly increased volume growth in Flakliden (Figure 10). Nutrient addition increased silvicultural costs, and lowered economic returns. According to our results, the increase in volume growth due to nutrient addition more than offset the economic cost due to loss in wood density and tracheid length. Taking log grading into account, however, the F_{55} regime resulted in higher net present values than those of the S_{80} regime at 0%, 3% and 5% interest rates.

4.3 Integrating bioenergy production into forest management optimization: energy wood from young Scots pine stands (III)

Forest bioenergy has become an increasingly important aspect of stand management. Study **III** integrates forest bioenergy production with conventional stand management in an optimization framework. The optimizations were applied to 15 Scots pine (*Pinus sylvestris* L.) stands in Finland. Stand development was based on the PipeQual stand simulator. The simulation-optimization system OptiFor was developed for assessing the effects of forest bioenergy policies on energy wood from young stands.

Conventional forest management (Policy 0) served as a benchmark (the optimal policy for timber production only) for comparison to alternative policies for energy wood production. Policy I was designed for profitable energy wood harvesting, which means that the first thinning will be treated as a precommercial thinning for energy wood production (small size trees from precommercial thinning) if the net income from the energy wood harvest is positive. Policy II assumed that the first thinning for energy wood production is compulsory. In other words, no matter how unprofitable energy wood harvesting is, the first thinning is always conducted as a precommercial thinning.

The optimal solutions maximizing bare land value indicate that in sparse stands (stands 1-2, 4-5, 7-8, 10-11, 13-14), conventional forest management regimes (Policy 0) were still optimal. In dense stands (stands 3, 6, 9, 12, 15), a forest bioenergy policy that included compulsory energy wood harvesting (Policy II) turned out to be optimal (Tables 2 and 3). Policy I, which was designed to result in profitable energy wood harvest operations as such, led to lower financial returns (Table 3).

In addition, our results show that precommercial thinning somewhat reduced the proportion of sawn wood grades for stands in fertile sites. For less fertile sites, the changes were insignificant. According to our results, precommercial thinning increased branch diameter growth. Policy II resulted in thicker branches, a higher crown base and a lower crown ratio at the second thinning than did Policy 0. The most significant changes in branch thickness and crown base appeared at the most fertile site. The thickest dry branch increased by 7% (0.13 cm), and the height of the crown base increased by 9% (0.6 m).

Table 3. Bare land value (€ ha^{-1}) based on different energy wood policies for 15 Scots pine stands at a 3% interest rate (Study **III**).

Stand	P0	PI	PII
1	**876**	853	839
2	**801**	779	783
3	717	714	**730**
4	**1548**	1519	1471
5	**1440**	1416	1412
6	1274	1297	**1338**
7	**3714**	3623	3606
8	**3638**	3546	3553
9	3336	3336	**3495**
10	**481**	473	443
11	**413**	403	407
12	302	343	**350**
13	**2400**	2373	2341
14	**2288**	2241	2279
15	2088	2062	**2188**

Note: P0 denotes conventional forest management, PI is Policy I, and PII is Policy II. Bold font highlights the highest bare land values of the three policies.

4.4 A comparison of carbon assessment methods for optimizing timber production and carbon sequestration in Scots pine stands (IV)

Estimating changes in forest carbon stocks and carbon balance differs for different forest carbon pools or various estimation methods. Study **IV** compared three carbon assessment methods for optimizing timber production and carbon sequestration. The six example stands were selected from Study **III**. Forest carbon stock was assessed based on stem carbon (C I), biomass expansion factors (C II), and a process-based model (C III), respectively. In this study, the average carbon stock was calculated as the sum of the annual carbon stock divided by the length of rotation (Richards and Stokes 2004). In addition, we computed the mean biomass production based on biomass removals from harvests and the length of rotation.

Comparison of carbon assessment methods and economic sensitivity analyses indicate that changing carbon assessment methods leads to very different optimal thinning regimes and average carbon stock. Given a carbon price of €40 t^{-1} (equivalent to €10.9 t^{-1} CO_2) and a 3% discount rate, the highest average carbon stock was obtained with CII. In general, the average biomass production for the optimum solutions with CII was higher than that for the optimum solutions with CIII (Figure 11). The differences in average biomass production between CII and CIII were more significant than those in average carbon stock. CIII led to less frequent thinnings and shorter rotation in the optimum solutions than did CII. Increasing the carbon price from 0 to €200 t^{-1} resulted in longer rotations and significantly increased average carbon stock, especially when carbon was assessed with CII.

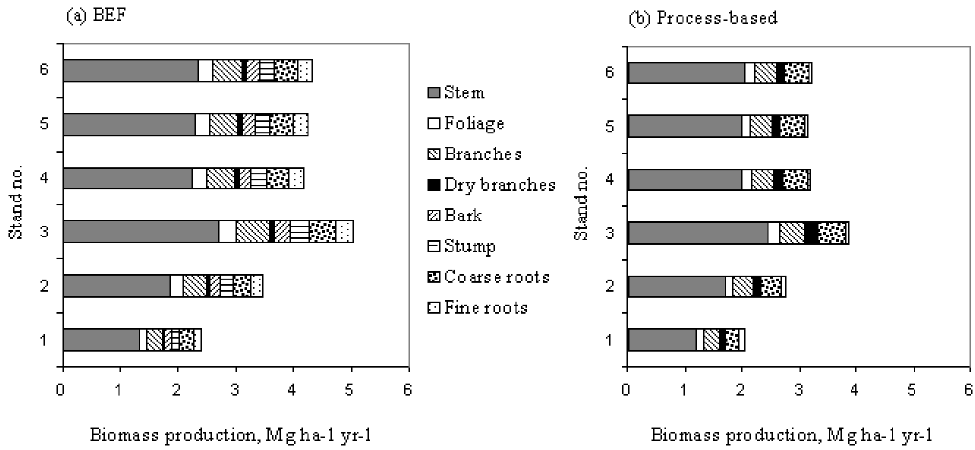

Figure 11. Mean biomass production by tree compartment based on BEF (biomass expansion factor) and process-based methods for six Scots pine stands with a carbon price of €40 t^{-1} at a 3% interest rate (Study **IV**).

5 DISCUSSION

5.1 Rotation length

The traditional question of stand management concerning the length of rotation was investigated for timber production (**I**, **II**) and non-timber production (**III**, **IV**). Our results in Scots pine (**I**) and Norway spruce (**IV**) stands confirm the negative relationship between rotation and interest rate (Johansson and Löfgren 1985, Montgomery and Adams 1995). The richer the site or the lower the initial density of the stand, typically the shorter the optimal rotation (**I**). The results of Study **I** also support the Scots pine study by Hyytiäinen et al. (2005) in that site quality and initial density characteristics strongly affect the optimal rotation. High within-stand competition at early ages decreases the diameter growth of individual trees and thus tends to increase rotation length for initially dense stands (**I**). Clear-cutting Norway spruce stands after the majority of stock trees have reached sawlogs dimensions is optimal due to the wide difference between sawlogs and pulpwood prices. Optimal rotation age seemed to be more sensitive to initial density than to site fertility. In addition, our results in Study **II** indicate that the thinning regimes with longer rotation lengths resulted in higher values of annual volume increment and higher values of wood properties.

Many forest managers expect a smaller sawlog volume increment and shorter rotation if the stand has been precommercially thinned (Pothier 2002). The positive effects of precommercial thinning on diameter and volume growth at the first commercial thinning were reported for balsam fir by Pothier (2002), and for lodgepole pine by Johnstone (2005). They pointed out, however, that no significant differences occurred in merchantable volume at maturity (Pothier 2002), or even after 20 years (Johnstone 2005). Meanwhile, Pothier (2002) found that the effect of precommercial thinning on rotation length depends on the management goals; these results are in line with those of Study **III**. With compulsory energy wood harvesting, the rotation length was somewhat shorter for dense stands.

Several previous studies (e.g., van Kooten et al. 1995, Romero et al. 1998, Huang and Kronrad 2001) have reported on the relationship between rotation and decision-making criteria concerning timber production and carbon sequestration. That is, the optimal rotation that maximizes joint timber and carbon sequestration is longer than the Faustmann rotation, but shorter than the MSY (maximum sustainable yield) rotation. Their studies simplified the optimal rotation problem as a non-thinned management regime and assessed forest carbon only for the stem. Our results in Study (**IV**) confirmed the findings of van Kooten et al. (1995) in that a decrease in the carbon emission rate shortened the optimal rotation. In addition, we also agree with the findings of van Kooten et al. (1995) and Backéus et al. (2006) that a high carbon price may restrict harvesting. In contrast to their studies, however, our results in Study **IV** show that the optimal joint production rotation could be shorter than the Faustmann rotation due to the different number of thinnings when carbon was assessed with a process-based model for Scots pine stands. Moreover, the optimal rotation was longer than the MSY rotation at a lower discount rate (e.g., 2%) or a higher carbon price (e.g., €200 t^{-1}).

5.2 Thinning and fertilization

In Study **I** we present new results for Norway spruce in that the optimal number of thinnings is sensitive to changes in the interest rate for sparse and moderately dense stands, but less sensitive for dense stands. This is a consequence of the difference between roadside prices of sawlogs and pulpwood, along with fixed costs, and of the effects of thinning response and mortality. Our results in Study **I** also support previous studies that at a 3% interest rate, two or three thinnings are typically optimal for Norway spruce (Risvand 1969, Solberg and Haight 1991, Valsta 1992b, Hyytiäinen and Tahvonen 2002) as well as for Norway spruce and Scots pine mixtures (Pukkala et al. 1998, Vettenranta and Miina 1999). Typically, the lower the initial density or the higher the interest rate, the lower the number of thinnings (Kilkki and Väisänen 1969, Solberg and Haight 1991, Valsta 1992b, Hyytiäinen et al. 2005). The number of thinnings decreases as the interest rate rises for Norway spruce (Solberg and Haight 1991, Valsta 1992b). For Scots pine, the optimal number of thinnings increases with juvenile density, but is less sensitive to changes in the interest rate (Hyytiäinen et al. 2005). When energy wood from precommercial thinning was taken into account, our results in Study **III** indicate that the total number of thinnings decreased if the first thinning was an energy wood harvest. According to Study **IV**, the optimal number of thinnings was about the same with CI (stem carbon) and CII (BEF method) as with the joint timber and carbon objective. However, less frequent thinning turned out to be optimal with CIII (a process-based method).

Many earlier studies in Finland have reported that late first thinnings, rather than conventional stand management, are optimal for Norway spruce (Valsta 1992b, Hyytiäinen and Tahvonen 2002) as well as for Norway spruce and Scots pine mixtures (Pukkala et al. 1998, Vettenranta and Miina 1999). Our results in Study **I** indicate that the timing of the first thinning is sensitive to site quality and stand characteristics. In contrast to earlier studies, the first thinning tends to come early for dense stands. In addition, our results in Study **III** show that that the requirement of a profitable energy wood harvest is irrational and may lead to a very early and extremely low intensity first thinning.

The results in Study **I** are in line with those of Thorsen and Helles (1998) in that the optimal thinning intensity decreased as the optimal number of thinnings increased. In Valsta (1992b), the first thinning was sensitive to initial density in terms of the thinning rate and timing, but the later thinnings and growing stock level were insensitive to initial density. As an extension of previous studies, we found that the optimal thinning intensity is insensitive to the interest rate for initially dense stands in the first thinnings (**I**). In addition, our results (**I**) agree with those of earlier studies (Valsta 1992b, Pukkala et al. 1998, Vettenranta and Miina 1999, Hyytiäinen and Tahvonen 2002) in that basal areas before thinnings were larger than those in Finnish silvicultural recommendations (Tapio 2001).

Some reports suggest that when wood properties are taken into account, less frequent and intensive thinnings are favorable (Pape 1999a,b). Our results (**II**) indicate that, compared with other management regimes, heavy thinning and a short rotation may significantly decrease the average wood density, tracheid length and latewood proportion of harvested trees. In addition, the less desirable heavy thinning regimes also imply that thinnings which are too heavy and too early may decrease wood density and tracheid length as well as reduce economic returns. This result is in line with that of Jaakkola et al. (2005b) in that intensive management appears to reduce tracheid length and mean ring density.

According to Study **III**, the intensity of energy wood harvesting was in the range of 40% to 51%. The density after energy wood harvesting was close to the target density recommended by Varmola and Salminen (2004). Pohjola and Valsta (2007) reported that lighter, frequent thinnings and longer rotation was optimal for timber production and carbon sequestration based on the empirical growth model MOTTI (Hynynen et al. 2002). However, when we assessed carbon with the process-based model PipeQual (Mäkelä 1997, 2002, Mäkelä and Mäkinen 2003), our results (**IV**) disagreed with the optimization results reported by Pohjola and Valsta (2007) due to the different initial stands, growth model and carbon assessment method used.

Some studies have reported that for conifer species, thinning from above or from both ends of the diameter distribution is typically superior to conventional thinning from below (Haight 1987, Haight and Monserud 1990, Solberg and Haight 1991, Valsta 1992a,b, Eriksson 1994, Pukkala et al. 1998, Pukkala and Miina 1998, Vettenranta and Miina 1999, Hyytiäinen et al. 2004, 2005). Our results (**I**) support the findings of the above studies in that this thinning type is more advantageous than thinning from below when the interest rate is above 1%. In addition, our results indicate that thinning from below is advantageous at first thinning only for low interest rates (e.g., 1%). Carbon assessment methods may also influence the type of thinning (**IV**): thinning from below was optimal for the dense stand with CI (stem carbon) and CII (BEF method), but the type of thinning was later changed to thinning from above with CIII (process-based method).

Earlier studies have shown that although fertilization accelerates growth, the impact of this acceleration on wood density (Jaakkola et al. 2006) and tracheid properties (Jaakkola et al. 2007) is insignificant. This raises the question of whether intensive management with nutrient addition would be profitable as a management alternative. The Flakaliden example in Study **II** indicates, as do other results from the same site (Mäkinen et al. 2002), that wood properties may indeed change considerably if extreme nutrient addition is applied. On the other hand, Study **II** suggests that an increase in volume growth may compensate for impaired wood properties; in this example, the volume size more than doubled for the rotation periods observed. Because of the parameterization method used, however, these results (**II**) apply to analyses of the development of wood properties only in the experiment at hand.

5.3 Forest bioenergy and the carbon balance

Our optimization results (**III**) indicate that carrying out the first thinning as an early energy wood harvest for initially dense stands is optimal. Requiring positive harvest revenue from the first thinning is common in practical stand management. Ahtikoski et al. (2008) also focused on determining the criteria for profitable energy wood thinning. Our results in Study **III**, however, reveal that an energy wood harvest plays a more important role as an investment in early thinnings.

The effects of precommercial thinning on growth and yield have been investigated based on thinning experiments for conifer cultures, such as Scots pine (Ruha and Varmola 1997, Varmola and Salminen 2004, Huuskonen and Hynynen 2006), balsam fir (Pothier 2002), and lodgepole pine (Jonestone 2005). In general, our results (**III**) on the effects of early thinnings on growth and yield were in line with those of earlier empirical studies for Scots pine (Mäkinen and Isomäki 2004, Varmola and Salminen 2004, Huuskonen and Hynynen 2006). We contribute to this literature by extending the analysis over the whole rotation period and by optimizing the timing and intensity of the thinnings with the option of an energy wood harvest for the first thinning. Some studies have reported that the strategy of precommercial thinning depends on the aims of stand management, such as even spacing, high yield, or both quality and yield (Vuokila 1972, Ruha and Varmola 1997, Varmola and Salminen 2004). Ruha and Varmola (1997) stated that the intensity of precommercial thinning depends on the aim of the first commercial thinning. Our results in Study **III** agreed with those of previous studies in that optimal thinning regimes vary with different forest bioenergy policies.

Huuskonen and Hynynen (2006) reported that early and light precommercial thinning (Hdom 3m, to a density of 3000 trees ha^{-1}) significantly increased the first commercial thinning removal by 40%. Postponing the first commercial thinning by ten years increased the present value of the stumpage revenues by 65% at a 4% interest rate (Huuskonen and Ahtikoski 2005, Huuskonen 2008). According to Varmola and Salminen (2004), precommercial thinning to 1600 and 2200 trees ha^{-1} was moderate. Because of the lack of dense stand data, we found no significant result in Study **III** similar to that in Huuskonen and Ahtikoski (2005). The current recommendation for energy wood production states that energy wood harvesting increases financial returns by 10% (Koistinen and Äijälä 2005). However, our results (**III**) indicated that the increase in financial returns by conducting precommercial thinning varies according to site conditions.

Precommercial thinning positively affects growth and yield, but may also negatively affect wood quality. Precommercial thinnings accelerate tree growth and, consequently, branch growth, which lowers timber grades for timber production from commercial thinnings and final felling. Economic analyses of thinning regimes and timber quality has been conducted for Scots pine (Hyytiäinen et al. 2004) and Norway spruce (**II**). Precommercial thinning was excluded in their studies. Other reports have described the positive effects of precommercial thinning on diameter growth and branch development for jack pine (Tong and Zhang 2005) and Scots pine (Varmola and Salminen 2004, Fahlvik et al. 2005), but lack financial information. Compared to earlier studies, our optimization results (**III**) show that the differences in the effects of precommercial thinning on the distribution of the end products were insignificant. Nevertheless, sawn wood grades were applied only in the simulations; in Study **III**, sawn wood prices were excluded and replaced with an average sawlog price.

Study **IV** expands the current understanding by analyzing how optimal thinning and rotation for timber production and carbon sequestration depend on carbon assessment methods in addition to financial incentives. Our results (**IV**) indicate that the choice of carbon assessment methods may dramatically change both optimal thinning regimes and net carbon cost. Therefore, an accurate and reliable carbon assessment method is crucial for optimizing timber production and carbon sequestration, as well as for planning efficient policy measures.

According to Harmon and Marks (2002), differences in including carbon pools led to conflicting results for stand level analyses. Our results in Study **IV** indicate that the estimation of mean biomass production also differs when using CII and CIII. The BEFs of stem and foliage (CII) are age-dependent, while roots and branches vary less in Scots pine (Lehtonen et al. 2004). The BEF method disagrees with the process-based method (CIII), especially in branch biomass estimation, where branch biomass is a function of crown length and foliage biomass (Mäkelä 1997).

Different types of tree growth models may also yield conflicting results. Using the empirical stand simulator MOTTI (Hynynen et al. 2002), Pohjola and Valsta (2007) found that lighter postponed thinnings and lengthened rotation became optimal. Based on a gap-type model, Liski et al. (2001) stated that longer rotation length would be favorable to carbon sequestration for Scot pine. Our results (**IV**), however, show that including optimal thinning and employing different carbon assessment methods did not lengthen the optimal rotation. Using another process-based ecosystem model (Kellomäki and Väisänen 1997), Briceño-Elizondo et al. (2006) found that a proper thinning regime can increase forest carbon stock without lengthening the rotation. Our more comprehensive optimization-based results (**IV**) confirmed their findings that optimal thinning plays a very important role in optimizing timber production and carbon sequestration.

Pohjola and Valsta (2007) included thinnings for timber and carbon optimization at the stand level. Their study used a constant biomass expansion factor of 0.7051 Mg m^{-3} for Scots pine and assumed a carbon emission rate of 100% (according to the Kyoto Protocol). However, biomass production by tree components varies considerably during rotation (Lehtonen et al. 2004). The use of a constant biomass expansion factor could overestimate biomass production in old age classes. The 100% carbon emission rate used in their study clearly increased carbon taxes so that earlier and heavier thinnings become unprofitable. By contrast, the time-dependent carbon emission rates used in Study **IV** lowered discounted carbon taxes. Thus, earlier and heavier thinnings turned out to be optimal.

5.4 Applicability of OptiFor and future developments

In practical forestry, the remaining trees should be reasonably evenly distributed irrespective of the thinning type. Increased attention to tree selection, such as with thinning from above, may require the marking of trees for removal and thus raise costs. On the other hand, thinning from above may, for some stands, result in additional logging damage. However, our computations (**I**, **III**, **IV**) did not take into account the higher costs or greater risk of damage due to thinning from above. Accounting for these effects may result in lighter thinnings. In Study **II**, the thinning regimes were simulated rather than optimized. An economic optimization model was excluded from Study **II** because of the need for further development at the time of the current PipeQual model. Taking economic optimization into account offers promise in analyzing the effects of thinning and rotation on wood properties with optimized management regimes.

According to Karjalainen et al. (1994), one third of carbon is released immediately during the wood production process. This was employed in Liski et al. (2001), but was not taken into account in Study **IV**. Obviously, taking into account carbon emission in the production process will increase the discounted carbon tax. Such an increase in discounted carbon tax may postpone thinnings and reduce the intensity of thinnings. In addition, Study **IV** excluded soil carbon and energy wood production, which could also affect the optimal thinning regimes and net carbon cost.

Finnish forestry statistics (Finnish Statistical Yearbook of Forestry 2008) show that the potential of energy wood from logging residues and clear-cuts is greater than from precommercial thinning. Logging cost models for forest bioenergy wood production have been developed for logging residues (Nurmi 2007). In the future, it would be interesting to investigate optimal thinning regimes for energy wood from logging residues in addition to early thinnings (**III**). Energy wood production may lead to changes in carbon sequestration. In addition, the energy wood price is rising with the continued consumption of energy wood. Study **III** took none of these effects into account, so future studies that include forest bioenergy production and carbon benefits, as well as a sensitivity analysis of energy wood prices could prove interesting as well. The comparison of carbon assessment methods (**IV**) indicates that changing carbon assessment methods led to very different optimal thinning regimes and average carbon stock. Including all forest carbon pools for optimizing timber production and carbon sequestration, as well as energy wood production and carbon balance in future studies could prove interesting.

The numerical studies in this thesis extended our current knowledge and understanding of the relationships between wood science, forest ecology, and forest economics. The OptiFor simulation optimization system was tested by comparing random search (RS), which uses the PPLMC random number generator (Law and Kelton 1982) and Osyczka's direct and random search (DRS) algorithms (Figure 12). The validation shows that the DRS algorithm used in OptiFor is clearly more efficient. The result of the comparison is well in line with those of Valsta (1990).

The development and applications of OptiFor in this dissertation show that the ecological-economic modeling approach we applied may improve research by using a scenario approach, and consequently improve the applicability of ecological models. Meanwhile, complex ecological models offer detailed ecological reasons to interpret economic optimization solutions. Such an integrated simulation-optimization approach provides greater understanding and knowledge of forestry practice. Future developments of OptiFor will focus on applications in forest and natural resources management, such as regeneration, fertilization, biodiversity, bioenergy, and soil carbon. Future developments will also take into consideration applications of alternative optimization methods, such as population-based methods, as well as adaptive optimization methods.

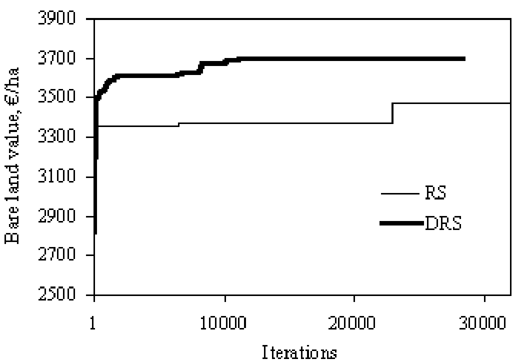

Figure 12. Comparison of Osyczka's direct and random search (DRS) and random search (RS) algorithms for maximizing bare land value (€ ha^{-1}) at a 3% interest rate.

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