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On the economics of boreal Scots pine management under climate change

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Academic dissertation

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This dissertation aims to develop the economics of even-aged Scots pine (*Pinus sylvestris* L.) management. In our economic-ecological model, a detailed process-based forest growth model is connected to an economic description of stand management. The process-based growth model is able to describe forest growth in management regimes and climate conditions previously not experienced, because it applies causal relationships and feedbacks instead of statistical correlations. Optimization is carried out with an effective general pattern search algorithm. The optimized variables include rotation length, initial stand density, and the timing, type, intensity, and number of thinnings. Essential model details include the quality pricing of timber and detailed harvesting cost functions. Integration of carbon subsidy systems into the model enables the determination of the economically optimal carbon storage with various carbon price levels. Finally, the growth model is extended to include a direct link between climate change and tree growth, to optimize stand management in a changing climate.

The dissertation thesis is composed of a summary section and three articles, which produce a coherent and comprehensive picture on the optimal stand management of Scots pine in the relevant growth conditions of Fennoscandia. The results demonstrate the necessity to simultaneously optimize all stand management variables, and the advantages of having a detailed model. Optimal stand management is shown to be sensitive to growth conditions, interest rate, and management objective, along with the design of the carbon subsidy system and the subsidy level. The stand-level analysis is additionally extended to the national level, and adapting forest management was found to potentially be a cost-efficient method for carbon abatement in Finland. Furthermore, the optimal adaptation of stand management in a changing climate remarkably improves the economic surplus from forestry.

Keywords: stand-level optimization, forest economics, optimal carbon storage, optimal adaptation to climate change, process-based growth model, generalized pattern search

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Finally, Jepa, the wise dragon. Words could never be enough to express my gratitude. ♥

LIST OF ORIGINAL ARTICLES

This thesis consists of an introductory review followed by three research articles. These papers are reproduced with permission from the publishers.

I Tahvonen, O., Pihlainen, S., Niinimäki, S. (2013). On the economics of optimal timber production in boreal Scots pine stands. Canadian Journal of Forest Research 43(8): 719–730.
http://dx.doi.org/10.1139/cjfr-2012-0494.

II Pihlainen, S., Tahvonen, O., Niinimäki, S. (2014). The economics of timber and bioenergy production and carbon storage in Scots pine stands. Canadian Journal of Forest Research 44(9): 1091–1102.
http://dx.doi.org/10.1139/cjfr-2013-0475.

III Pihlainen, S., Tahvonen, O., Mäkelä, A. (2017). Economics of boreal Scots pine stands in a changing climate. Manuscript.

AUTHOR’S CONTRIBUTION

Sampo Pihlainen was responsible for compiling the summary of this thesis. The author participated in the planning of Studies **I**–**III** and in developing the economic optimization framework in Study **I**. The author conducted most of the economic optimization framework development in Studies **II**–**III**. The author produced all optimization results in Studies **I**–**III**. The author produced the preliminary version of the manuscript text in Study **I** and participated in interpreting and discussing the results. In Studies **II** and **III**, the author did most of the writing, along with interpreting and discussing the results.

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INTRODUCTION

Background and motivation

Climate change is one of the main challenges facing mankind. Increasing forest carbon storage may prove to be a crucial key in climate change mitigation, as forest carbon sinks are immense and hold growth potential (Pan et al. 2011; IPCC 2014, p.101). However, to fully utilize this potential, it is of utmost importance to optimally adapt forest management, taking into account changing growth conditions and the carbon storage objective. This thesis develops the ecological-economic model needed in this task by proceeding incrementally from the simplest possible model formulation in Study **I** to the high complexity of Study **III**.

Scots pine (*Pinus Sylvestris* L.) is one of the most abundant tree species in the world, with an outstandingly wide range across all of Eurasia (Boratynski 1991). Its economic significance has been huge, especially in the Nordic countries. Furthermore, its significance in the boreal region is proposed to increase with climate change, as the growth potential of the heat-tolerant Scots pine is predicted to improve (Lutz et al. 2013). The wide distribution of Scots pine encourages the study of enhanced carbon storage in Scots pine forests as a means of carbon abatement.

Given the huge importance of Scots pine in the timber production and carbon storage of Nordic countries, its optimal stand management is surprisingly inadequately studied. Furthermore, the few existing studies commonly oversimplify the framework by neglecting the optimization of thinnings, which, in the case of Scots pine, may provide over 40% of total timber revenues. Another common feature is the use of statistical-empirical growth models, which are unable to plausibly depict forest growth in conditions outside the validated range of the model.

The optimization of Scots pine stand management in various climatic conditions calls for an interdisciplinary framework, connecting a highly detailed process-based growth model to a theoretically sound economic description of forest management, and applying efficient optimization methods. It provides optimal stand management at various carbon subsidy levels and enables the determination of aggregate-level cost-efficient carbon storage cost plans, and thus the comparison of carbon storage costs to other means of carbon abatement. Furthermore, it enables the determination of optimal climate change adaptation in forest management.

Economics of stand-level forest management

Economic optimization of forest management has traditionally focused on stand-level management. A stand is a homogenous parcel of forest, and considered to be the smallest operational unit in forestry. However, optimal stand-level results can be aggregated to the forest level, when the effects of scale are assumed to be negligible. The interdisciplinary approach to economic optimization of stand management entails the use of ecological models to specify forest stand growth.

Stand growth models can be classified according to five properties. First, models can be specified in even-aged or uneven-aged context, the former including compulsory clearcuts. However, Tahvonen (2009; 2015) presents a model where both management regimes are possible. Second, the unit of prediction may be the complete stand, an age or size class, or an individual tree. Third, the model is distance-dependent if it employs tree location data. Fourth, the model is stochastic if it includes events with multiple optional outcomes that are given certain occurrence probabilities; otherwise the model is deterministic. Fifth, the model is statistical-empirical or process-based, the former meaning reliance on statistical correlations based on some experimental plot data, and the latter being (also) based on causal relationships and feedbacks in tree physiology (Landsberg and Sands 2011).

In process-based models, biomass production is allocated to the bole, branches, roots, and foliage following certain rules and liabilities. These models apply causal relationships and feedbacks instead of statistical correlations. The main benefit of using these complex models is their capability to predict forest growth in states outside the validity of statistical models. Furthermore, they enable detailed information on timber quality, as they are able to provide accurate information concerning branches that may deteriorate timber value. Practically all process-based models are hybrids, meaning that they have some empirical components included, in addition to process-based ones.

The optimization of stand management can be carried out with various types of stand growth models. Most previous stand-level optimization studies have been carried out with whole-stand models (Amacher et al. 2009). In such models, the stand volume is a function of stand age, and rotation length is the only optimized variable. One main simplification in these models is the omission of thinnings. When optimizing the stand management of a tree species like Scots pine, where thinnings may provide 40% of the overall revenue, this omission may lead to unwarranted conclusions. Even when the whole-stand model is extended to include stand density as an independent variable, the description of stand structure is too aggregated to realistically describe stand development. This is especially pronounced when optimizing the type of thinnings, i.e. the proportion of trees removed from various diameter classes (thinning from above or from below) (Hyytiäinen 2003).

Early studies optimizing the stand management of Scots pine using a whole-stand model include Nyyssönen (1958), and Kilkki and Väisänen (1969). The study by Gong (1998) used a whole-stand model to examine the optimal initial density and stand management of Scots pine stands in northern Sweden. An extended whole-stand model was applied in Brukas and Brodie (1999) for Scots pine stand management in Lithuania. The study of Lu and Gong (2003) applied a whole-stand model with no thinnings, and examined optimal Scots pine rotations under the effect of stochastic price variations. A similar model was used by Brazee and Bulte (2000) using Dutch data.

In individual-tree models the level of detail is one tree (or a number of distinct subject trees), which is characterized by a number of state variables. The state variables are influenced by growth, mortality, harvesting, and inter-tree competition. Individual-tree models have been used in Scots pine stand management optimization in Eriksson (1999), Pukkala and Miina (1998), and Hyytiäinen et al. (2004; 2005). The model in Pukkala and Miina (1998) is distance-dependent assuming one thinning. The thinning prescriptions in the optimization were more general in the studies by Hyytiäinen et al. (2004; 2005).

The aforementioned studies on the optimization of Scots pine stand management fall short in detail in many aspects. First, they limit their focus on only specific site types and, thus, fail to provide a comprehensive picture on the optimal stand management at the national or Fennoscandian level. Second, the thinning prescriptions are either non-existent or over-simplified for full consideration of the possibilities of optimized thinning. Commonly, the number, intensity, timing, or the type of thinnings is constrained without any economic or ecological justifications. Third, only two earlier studies include quality pricing in the model. Fourth, the previous studies use statistical-empirical models that are validated only in the range of the original sample plot conditions. Hyytiäinen et al. (2004) is the only previous study to use a process-based model, with the capability of reliably describing unprecedented conditions also, in the economic optimization of Scots pine stands.

The forest growth model used in the present study is an even-aged, individual-tree, distance-independent, deterministic, process-based model developed in Mäkelä (1997), Mäkelä (2002), and Mäkelä and Mäkinen (2003). The model is able to predict the growth of trees in all relevant Fennoscandian growth conditions, and in a changing climate. The model enables comprehensive optimization of the number, timing, type, and intensity of thinnings. Utilization of quality pricing for timber is enabled by the model's detailed information on branches. Study **I** extends the framework of Hyytiäinen et al. (2004) by varying the site type, optimizing initial density, and updating the thinning specifications along with the optimization algorithm.

Economic optimization of carbon storage in forest stands

Carbon storage is a positive externality of forestry that can be internalized for example by paying subsidies for stored carbon. Currently, New Zealand, for example, has a carbon subsidy scheme in place, providing incentives for forest owners to increase and sustain the carbon stocks in their forests (Adams and Turner 2012).

The traditional Faustmann (1849) framework, describing the economically optimal forest management, can be extended to include revenues from carbon storage, in addition to revenues from timber. The economic literature on stand management optimization with subsidies on carbon storage is well established (e.g. Plantinga and Birdsey 1994; van Kooten et al. 1995), but the focus has only been on the optimization of rotation age (e.g. Hoen and Solberg 1997). Studies by Gong and Kriström (1999) and Caparrós et al. (2003) optimize the rotation age for Scots pine stands with carbon subsidies in northern Sweden and Spain, respectively. This level of detail (only one optimized stand management variable) is, however, not satisfactory for a sufficiently realistic description of optimal carbon storage, because it does not enable the control of the forest carbon stock during the rotation. To achieve this, the optimization of initial stand density and thinnings is essential.

Studies optimizing stand management with carbon storage and thinnings are few. The studies by Huang and Kronrad (2006) for loblolly pine and Niinimäki et al. (2013) for Norway spruce are rare examples. The latter study uses a framework, which is the preliminary version of the framework used in Study **II**. It includes the necessary optimized variables, regarding initial density and thinnings, in addition to the rotation length. Furthermore, it also uses a process-based growth model, thus enabling reliable predictions of stand growth even in stand structures not found in the original sample plots. However, the study by Niinimäki et al. (2013) neglects the carbon storage in branches, foliage, and dead trees and is, thus, unable to provide results on the significance of these carbon pools to the optimal results. In addition, they do not include the possibility for energy wood removals. Finally, they do not take their analysis of carbon storage costs to the national level, which is essential for comparing the cost-efficiency of forest carbon stock enhancement to other means of carbon abatement. The results of their study indicate the importance of thinnings in the optimal adaptation of stand management to provide optimal carbon storage. They include several site types in the analysis, and find thinnings to be especially important at poor sites, which also seem to provide the more cost-efficient means to increasing carbon storage compared to fertile sites.

The study of Goetz et al. (2010) provides an optimization of the harvesting and planting intensities of Scots pine stands, using an uneven-aged forest management framework. This framework, abandoning the assumption of compulsory clearcuts, presents a different setting for forest management optimization compared to the even-aged framework in this dissertation thesis. Furthermore, Goetz et al. (2010) fix the harvesting and planting interval to ten years. Their results show that the optimal number of trees in the stand increases with carbon price. In addition, they find carbon storage costs to be low in comparison with figures presented in earlier meta-analyses (Richards and Stokes 2004; van Kooten and Sohngen 2007). The study of Zhou (2001) analyzes the optimal stand management of Scots pine in Sweden, fixing the number of thinnings to one, but optimizing the initial density. He finds the initial density to increase with the carbon price. Furthermore, this increase is found to be more pronounced at poor sites.

Pohjola and Valsta (2007) is the only earlier study including thinning prescriptions among the optimized variables in Scots pine stand management with carbon storage. They report the modification of thinnings to be the most important factor when aiming to increase the average carbon storage, with the change in rotation length having only a minor role. Despite having a more detailed model compared to their predecessors, their study also has limitations. They use a statistical-empirical model incapable of providing reliable results outside the sample plot conditions used to estimate the model. This is troublesome, as some of their optimization results imply a markedly high stand density compared to those in the sample plots used in the model estimation. They also use a model with an immediate release of carbon into the atmosphere in the harvests, neglecting the potential of enhancing the carbon stock by producing longer-lasting products from timber.

The model used in Study **II** enables the detailed optimization of thinnings and initial density, and the inclusion of carbon storage in branches, foliage, and dead trees in the carbon pools. Compared to the model in Pohjola and Valsta (2007), which only includes saw log and pulp as timber assortments, the process-based growth model used in Study **II** enables the determination of five timber assortments. In addition, Study **II** examines the cases of accurate product decay and non-decaying products. A further extension to the framework in Pohjola and Valsta (2007) is the possibility to use harvest residue for bioenergy. Finally, Study **II** provides the national aggregate supply curves for carbon storage, and compares the carbon abatement costs of forestry to other sectors.

Economics of forest management adaptation to climate change

Determination of the economically optimal adaptation of forest management to a changing climate is a challenging task. It necessitates an ecological model that is able to simulate forest growth in management regimes and climate conditions not experienced before, and an economic model allowing the forest management to change in the course of changing growth conditions.

An abundance of studies can be found on the effect of a changing climate on forest growth, timber production, and carbon storage from a silvicultural point of view. These studies commonly do not include the possibility of management adaptation in their analysis. However, management adaptation can have a major effect, as is evident in the study by Sohngen and Mendelsohn (1998). They study the effect of climate change on the timber markets of the United States. They use a nation-wide dynamic model of timber markets and solve the equilibrium prices, the regenerated species, and the harvests. Furthermore, they determine the price path that leads to the new steady state. By including optimal adaptation in their model, they are capable of yielding a result, where the harmful effects in the environment caused by the changing climate are dampened by the dynamic market adjustments. Although they allow successive rotations to differ in length, their model keeps forest management at such a stylized level that detailed stand-level results cannot be derived from their study.

Adaptation to climate change by conducting economically optimal species selection in the changing growth conditions has been studied e.g. by Hanewinkel et al. (2010; 2012). Furthermore, the study by Guo and Costello (2013) compare this “adaptation of forestry on the extensive margin” to “the adaptation on the intensive margin”, the latter denoting the adaptation of forest management while maintaining species selection fixed. They report the importance of the latter being minor. However, their model allows only rotation length altering as an adaptation measure. For Nordic species and growth conditions, neglecting the modification of thinnings and the initial density crucially undermines the adaptation possibilities. Study **III** focuses on forest management optimization, but notes that species selection optimization is unwarranted without detailed optimization of the stand management of relevant tree species in changing conditions.

The optimal adaptation of forest management is studied in some ecological and silvicultural studies. The common approach is to use a number of management scenarios, thus failing to freely optimize the management. Although the study by Garcia-Gonzalo et al. (2008) performs a multi-objective regional optimization using a process-based model and a wood product model, they use fixed thinning strategies. They report the preferable regional management prescriptions to include higher stocking and postponed harvests when comparing to the recommendations in the current, non-changing climate. Another regional model is used by Nuutinen et al. (2006), who maximize sustained yield (MSY) in mixed-species forests. They apply various management prescriptions and climate change predictions, which together form six different scenarios. A changing climate in their results brings a higher MSY and increases the importance of thinnings. Pure Scots pine stands have also been studied in a changing climate, and results imply increasing timber yield (Briceño-Elizondo et al. 2006a), increasing carbon stock (Briceño-Elizondo et al. 2006b), shortening rotation periods (Kellomäki et al. 1997), and earlier harvests (thinnings and clearcut) (Kellomäki and Kolström 1993).

Because of several shortcomings the aforementioned studies only provide a partial analysis on the economics of stand management. First, they do not systematically optimize forest management. Second, they lack the in-depth evaluation of scenarios by an objective function that would include timber production and carbon storage. Third, they commonly concentrate on a 100-year horizon (i.e. the focus is on one rotation only). Fourth, the choice of management scenarios rejects such alternatives that would produce less timber than the potential in current conditions. This represents an MSY-type of approach, which does not recognize that economic potential is not directly determined by the produced timber volume.

Extending the time horizon to include several dissimilar rotations includes a difficult aspect in the optimization. In steady growth conditions the analysis can be based on Faustmann-type formulation with equal rotations. With changing conditions this cannot be applied, and the management in subsequent rotations must be allowed to vary. The study by Goetz et al. (2013) tackles this problem using a framework of uneven-aged forestry and fixing the harvesting and planting period. They report the optimal stand density to increase with a changing climate in Spanish Scots pine stands. In the study by Härtl et al. (2016), the treatment schedules are optimized for two mountainous mixed-species forest regions. Their results recommend the reduction of growing stock levels under a changing climate. Pukkala and Kellomäki (2012) study mixed-species stands and optimize rotation length and the timing and intensities of thinnings. However, they fix the number of thinnings to two and assume all rotations to be identical, thus failing to provide insight into the gradual change in the optimal stand management due to climate change. Their results imply earlier harvests in a changing climate compared to the current climate with no climate change.

Study **III** is, as far as we know, the first study to optimize even-aged stand management in a way that allows subsequent rotations in a changing climate to be different. In addition, it is the first study to also include carbon storage as an objective in the economic optimization of even-aged forest management in a changing climate. Both of these contributions apply for any tree species, not only Scots pine.

Objectives of the dissertation

The general objective of this thesis is to develop the numerical optimization framework for the economic-ecological analysis of boreal forest management, taking into account the monetary value of timber, energy wood, and carbon storage, along with the effect of climate change on tree growth conditions.

The specific objectives of the three studies in this dissertation are:

Study I

- to further develop the economic-ecological optimization framework connecting a process-based model to a theoretically sound economic model on stand-level forestry
- to produce results on the optimal Scots pine stand management in Nordic conditions for various site classes
- to determine the efficiency gain of using economically optimal stand management instead of the management maximizing sustained yield (MSY)
- to study the role of timber quality and thinnings in the determination of optimal forest management

Study II

- to include optimal carbon storage into the process-based Scots pine economic optimization framework
- to compare the effects of various carbon subsidy systems on economically optimal initial density and harvesting
- to develop a model of a decaying carbon pool that includes carbon in live tree stems, branches and foliage, in dead trees, and in timber products
- to yield results on the optimal Scots pine stand management in Nordic conditions with carbon subsidy systems and to compare these results to current recommendations on forest management
- to present the conditions where the removal of harvest residue for bioenergy is optimal
- to present a nation-wide cost-efficient carbon storage plan
- to compare forest carbon storage costs to carbon abatement costs in other sectors
- to compare the economic outcomes of stand-level adaptation and afforestation as carbon storage methods

Study III

- to integrate a process-based growth model with a straight link between climate change and stand growth into the economic-ecological optimization framework
- to yield results on optimal Scots pine stand management in Nordic conditions with a carbon subsidy system in a changing climate
- to determine the value of forest management adaptation to climate change
- to determine the change in optimal timber yield and optimal carbon storage due to climate change

MODEL AND METHODS

Process-based growth model

The forest growth model used in this study is a distance-independent, individual-tree process-based model developed in Mäkelä (1997), Mäkelä (2002), and Mäkelä and Mäkinen (2003). The model has been parameterized for Scots pine. It was first used in connection with economic optimization in Hyytiäinen et al. (2004). The model contains four submodels that describe the stand, trees, whorls, and branches, and provide information on the dimensions and quality of stem and branches. Shading and crown coverage form interactions between trees that influence photosynthesis, natural mortality, and growth. Subject trees or tree classes define the stand structure. A tree class contains a variable number of similar trees scattered uniformly in the stand area. Owing to the complexity of the model, the number of the state variables becomes as large as 7921–18321, depending on the rotation period.

At a very general level, the dynamics of the process-based model may be presented as a discrete-time system of state and control variables. Let $z_{ij,t+1}$ describe the value of the state variable $j=1,...,m$ of trees in tree class $i=1,...,n$ at the beginning of year $t+1$. The process-based model determines this value as a function of the stand state and a possible harvest at year t. For each harvest $s=1,\dots,k$ at stand ages t_s, the fraction of trees harvested (or harvesting intensity) γ_{dt_s} is chosen separately for the dominant $(d=1)$, co-dominant $(d=2)$ and suppressed trees $(d=3)$. The summarization of the ecological model and its control, provided by harvesting intensities, as a set of difference equations and constraints, is as follows:

$$\begin{aligned} z_{ij,t+1} = {} & f\left(z_{11t},...,z_{1mt},z_{21t},...,z_{2mt},...,z_{n1t},...,z_{nmt},\gamma_{1t},\gamma_{2t},\gamma_{3t}\right), \\ & i=1,\dots,n,\ j=1,\dots,m, \end{aligned} \tag{1}$$

$$\begin{aligned} & \frac{h_{it}}{z_{i1t}}=\gamma_{1t},\ i=1,2,3,\ \frac{h_{it}}{z_{i1t}}=\gamma_{2t},\ i=4,5,6,7,\ \frac{h_{it}}{z_{i1t}}=\gamma_{3t},\ i=8,9,10, \\ & t=\ 0,\dots,t_k, \end{aligned} \tag{2}$$

where m denotes the total number of state variables per tree class, n the number of tree classes, $z_{i1t}, t=0,...,t_k$ the number of trees in tree class $i=1,...,n,$ and $h_{it}, t=0,...,t_k$ the number of harvested trees in tree class $i=1,...,n.$ The initial values of state variables $z_{ij0},\ i=1,...,n,\ j=1,...,m$ are otherwise given, but initial stand density N_0 is instead an optimized variable. See the *Model and methods* -section of Study **I** for further details concerning the model.

The original model specification developed in Mäkelä (1997), Mäkelä (2002), and Mäkelä and Mäkinen (2003) is, in any case, not simplified for the purposes of the economic analysis of our studies.

Economic description of stand management

The core of the economic model is the objective function for maximizing the (after-tax) present value of the forest owner's net revenues over an infinite horizon. In other words, we maximize the bare land value of the forest. In stable growth conditions this is straightforward, following the formula developed originally by Faustmann (1849). Studies **I** and **II** assume a current stable climate, and thus steady growth conditions. Study **III** assumes a changing climate, which, however, stabilizes to a steady state. Therefore, the optimization problem in Study **III** also necessitates the use of steady-state objective function during part of the planning horizon.

The optimized variables include the number of seedlings N_0, the timing of harvests t_s, $s = 1, \ldots, k$ (t_k denotes the timing of the clearcut and thus the rotation length), the number of harvests k, the intensity of harvests γ_{dt_s}, $d = 1, 2, 3$, $s = 1, \ldots, k$, and the intensity of utilizing harvesting residues and waste wood as bioenergy γ_{bt_s}, $s = 1, \ldots, k$ (only applied in Study **II**). A stylized version of the optimization problem in steady growth conditions can be presented as follows:

$$\max_{\left\{\substack{N_0, k, t_s, \\ \gamma_{dt_s}, \gamma_{bt_s}, \\ d=1,2,3, \\ s=1,\ldots,k}\right\}} J = \frac{-w + \sum_{s=1}^{k} b^{t_s} \left\{ \sum_{i=1}^{n} \left[\sum_{v=1}^{g} p_v D_{ivt_s} h_{it_s} + p_b D_{ibt_s} h_{it_s} \gamma_{bt_s} \right] - C\left(\mathbf{h}_{t_s}, \mathbf{D}_{t_s}\right) \right\} + \sum_{t=0}^{t_k} b^t p_c Q_t}{1 - b^{t_k}}, \tag{3}$$

subject to (1), (2), and non-negativity conditions for the state and control variables.

The numerator determines the discounted net revenues from timber and bioenergy production and carbon storage over one rotation. The revenues from the harvested trees h_{it_s}, $i = 1, \ldots, n$, $s = 1, \ldots, k$, are based on the tree dimensions D_{ivt_s}, and the prices p_v are determined separately for each timber assortment $v = 1, \ldots, g$. The harvesting costs $C\left(\mathbf{h}_{t_s}, \mathbf{D}_{t_s}\right)$, $s = 1, \ldots, k$ depend on the number of harvested trees h_{it_s}, $i = 1, \ldots, n$, $s = 1, \ldots, k$, and the amount of saw log, pulpwood, and waste wood in the harvest. The cost model for cutting and hauling is based on the time expenditures of various work phases (Kuitto 1994). The fixed harvesting cost is €100 in Study **I** and €300 in Studies **II** and **III**. The reason for this difference is that the level of fixed costs was reassessed after the completion of Study **I**, and €300 euros was found to be a more plausible estimate. The discount factor is denoted by $b=1/(1+r)$, where r is the annual interest rate. Parameter w denotes the stand regeneration costs. Regeneration is based on seeding and the cost is independent of the initial density and site type. Prices of timber assortments are roadside prices and the price for energy wood is a stumpage price.

In Studies **II** and **III**, carbon storage is given a monetary value via a subsidy-based instrument. The variable Q_t denotes the change in the carbon pool during year t and is multiplied with the carbon price p_c in the objective function ($p_c = 0$ in Study **I**). In Study **II**, the carbon pool includes all aboveground tree biomass, i.e. stem, branches, and foliage of alive and dead trees, harvest residue, along with timber products. The decay of dead trees is taken into account and differentiated for each tree compartment. In Study **III**, the carbon pool consists of standing merchantable timber and timber products. The reason for the smaller carbon pool in Study **III** was that enabling a changing climate necessitated certain simplifications in the model to ensure tractability.

In Studies **II** and **III**, the decay of timber products is taken into account in the carbon pool. Study **II** examines and compares two different carbon subsidy systems, the *gross* and *net subsidy system*. In the gross subsidy system, which rewards for the carbon stored in net forest growth, the carbon in timber products never decays. Implicitly, this assumes that society focuses its carbon regulation on the user side of the market. In the net subsidy system, which is determined by subtracting the carbon released from timber products from the carbon pool in a gross subsidy system, the carbon in timber products decays at a certain rate. This system is similar to the scheme currently enforced in New Zealand (Adams and Turner 2012), while the gross subsidy system is also shown to be theoretically sound (Tahvonen 1995). However, the New Zealand system assumes all carbon from trees to be released to the atmosphere at the time of harvest. We therefore contribute to the New Zealand system by including gradually decaying timber products, and thus produce results on a type of extended system also called for in New Zealand (Manley and Maclaren 2010). In our model specification, the forest owner may increase her carbon subsidies by increasing the biomass in her forest and by increasing saw log production, because products made of saw logs last longer than those made of pulpwood.

The optimization problem in Study **III** is more complex, because the changing climate alters the growth conditions. In this study, the climate is assumed to follow Bergström et al. (2011) during a 100-year transition period and to reach a new steady state thereafter (Figure 1). In our model for a changing climate, tree growth is directly influenced by increased temperature and an elevated CO_2 level in the atmosphere, along with enhanced nutrient turnover in the soil organic matter and the effects of drought. This implies a difficult optimization problem that, to my knowledge, is this far circumvented in the earlier literature.

It can be given as:

$$\max_{\left\{\begin{array}{l} N_{0a}, k_a, t_{sa}, \gamma_{dt_{sa}}, \\ d=1,2,3, s=1,\ldots,k_a, \\ a=1,2,3 \end{array}\right\}} J = W_1 + b^{t_{k_1}} W_2 + b^{t_{k_1}+t_{k_2}} W_3 + b^{t_{k_1}+t_{k_2}+t_{k_3}} J_{\psi}, \tag{4}$$

subject to similar constraints as specified by (1), (2), but separately for each rotation.

The variable $W_a, a = 1,2,3$ denotes the rotation-period -specific net present value from the rotations in the transition period and is given by:

$$W_a = -w + \sum_{s=1}^{k_a} b^{t_{sa}} \left[\sum_{i=1}^{n} \sum_{v=1}^{g} p_v D_{ivt_{sa}} h_{it_{sa}} - C\left(\mathbf{h}_{t_{sa}}, \mathbf{D}_{t_{sa}}\right) \right] + \sum_{t=0}^{t_{k_a}} b^t p_c Q_{ta}, \\ a = 1, 2, 3. \tag{5}$$

Note that in (4), the variable J_{ψ} denotes the bare land value determined by equation (3) in the future stabilized climate. The optimized variables are the same as in Study **I**, but their optimal values may end up being different in each of the rotations of the transition period and the future steady state.

Table 1 summarizes the model specifications in Studies **I**, **II**, and **III**. Emphasis has been given to incremental progress by proceeding step-wise towards a more detailed framework. This is essential to ensure model functionality and interpretations. First, the forest owner receives revenues only from the sale of timber (**I**), then also from carbon subsidies (**II**, **III**) and bioenergy sales (**II**). The process-based growth model first depicts current climate only (**I**, **II**), and then a changing climate (**III**). The carbon pool covers biomass in the stem and timber products (**III**), or also in the branches, foliage, and dead trees (**II**).

The simulation and optimization codes used in Studies **I**, **II**, and **III** are available upon request.

Optimization algorithm

For the studies in this thesis, the optimization was carried out with Matlab using pattern search, which is a derivate-free optimization algorithm (Kolda et al. 2003; The MathWorks, Inc 2013). The use of gradient-based methods was not possible because of model complexity. To ensure the discovery of the global maximum despite the potential non-convexities, a high number of initial guesses was needed, typically 50–100. Computation was very time-consuming, particularly when allowing the climate to change in Study **III**. Obtaining the optimal solution for initial density and harvesting in a changing climate for one site type and carbon price could take over 10 days despite simultaneously using 10 computer cores.

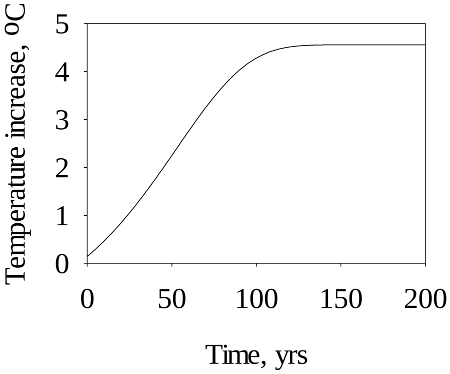

Figure 1. The hypothesized temperature change in Fennoscandia over the next 200 years.

Table 1. Model specification in Studies **I**, **II**, and **III**.

Study	**I**	**II**	**III**
Process-based growth model	X	X	X
Fixed costs: €100	X		
Fixed costs: €300		X	X
Bioenergy		X	
Timber quality pricing	X	X	X
Carbon subsidy system: NET		X	X
Carbon subsidy system: GROSS		X	
Carbon pool: merchantable timber		X	X
Carbon pool: branches, foliage, and harvest residues		X	
Carbon pool: dead trees		X	
Changing climate			X
Interest rate: 3%		X	X
Interest rate: 0–5%	X		

RESULTS

On the economics of optimal timber production in boreal Scots pine stands (I)

Study **I** sets out to determine the economically optimal way of producing timber in boreal even-aged Scots pine stands. Another motivation is to ensure a solid foundation for model extensions: a carbon storage objective in Study **II**, and changing growth conditions in Study **III**. The study advances systematically from the simplest model formulation to the most detailed specification. It yields separate results for various objectives, including maximum sustained yield (MSY), optimum with zero interest rate ("Forest rent"), and economic optimum with and without thinnings. This way the tractability of the results is ensured. This also gives insight into the dependency of optimal results on the objective chosen.

The high number of the simultaneously optimized variables enables a more exact determination of the optimal Scots pine stand management than is present in the earlier literature. Optimized thinnings are found to yield longer rotations, higher timber production, and better economic outcome. Results are determined for all relevant Nordic sites for Scots pine.

Using distinctive prices for each timber assortment, we obtain the result that optimal rotation does not necessarily shorten with increasing timber price. This conflicts with the generic Faustmann framework (Johansson and Löfgren 1985; Amacher et al. 2009). Furthermore, we find our results with quality pricing to question the culmination principle (Binkley 1987; Amacher et al. 2009), which determines the conditions where the economically optimal rotation may be longer than the rotation maximizing sustained yield. These results show that results and principles obtained using simple frameworks do not necessarily carry over to extended models.

The main contributions of the study include:

1. Detailed description of Scots pine management for various site productivity classes.
2. Results showing the role of timber quality, optimal thinning, and economic objective in Scots pine management.
3. Results showing that the effect of timber price and the applicability of the culmination principle developed in the context of the generic Faustmann model do not carry over to detailed extended rotation models.

The economics of timber and bioenergy production and carbon storage in Scots pine stands (II)

Study **II** extends the model developed in Study **I** by including a carbon subsidy scheme and the possibility for bioenergy production from harvest residue. To determine the economically optimal forest management, we maximize the net present value of the forest owner's net revenues from timber, energy wood, and carbon subsidies.

Results for optimal stand management are given depending on the level of carbon subsidies. Carbon storage decreases the present value of net revenues from timber and bioenergy production. The cost-efficiency of carbon storage in forests is compared with emission reductions in the industrial sector and afforestation of agricultural areas. Furthermore, carbon storage is optimized over various site classes.

In this study we find carbon storage to increase the rotation length, the optimal number of thinnings, and the optimal initial density. Timber yield increases with carbon storage up to a certain point. The harvest of logging residues to bioenergy is found to be optimal when carbon price is not more than 3.65 times the stumpage price of energy wood. Furthermore, storing additional carbon in Finnish Scots pine stands appears to be a cost-efficient option for realizing the Finnish carbon abatement targets. In addition, the marginal costs of carbon storage are low compared to earlier forestry studies (Richards and Stokes 2004; van Kooten et al. 2009). Finally, we investigate the economic rationale of afforestation in addition to stand-level carbon storage.

The main contributions of the study include:

1. A detailed picture of the economically optimal joint production of timber, carbon storage, and bioenergy in boreal Scots pine stands.
2. Results on the effects of various carbon subsidy systems and the price of carbon on optimal stand management and carbon storage in living biomass, dead trees, and timber products.
3. Results suggesting that stand management adaptation and afforestation may be the most cost-efficient methods for carbon abatement in Finland.

Economics of boreal Scots pine stands in a changing climate (III)

In Study **III**, we determine the economically optimal even-aged Scots pine stand management in a changing climate. Optimal stand management is not necessarily the same in consecutive rotations, because climate change alters the growth conditions. This makes the optimization problem difficult. Corresponding stand management optimization has not been carried out previously for any tree species.

The results for the changing climate, and concerning only timber production, show that with optimized thinning the forest rotation first lengthens and then shortens, but tends to remain longer than without climate change. Furthermore, the optimal number and intensity of thinnings increases. Without thinning the optimal rotation decreases monotonically. This difference in results with and without thinnings emphasizes their role in optimal adaptation. Interestingly, the character of the optimal results changes when including value for stored carbon: with optimized thinnings the rotation tends to shorten and without thinnings it initially lengthens and subsequently shortens. Timber production and carbon storage both increase remarkably with climate change, especially at poor sites.

Furthermore, optimal adaptation of stand management to changing conditions is found to yield significantly higher bare land values compared to forest management without adaptation. To achieve the full potential of gain in bare land values, all relevant stand management variables need to be optimized in a changing climate. On the one hand, neglecting thinnings, and on the other hand, applying stand management optimal in the future steady state already in a changing climate, lead to much smaller values of adaptation.

The main contributions of the study include:

1. A rather complete picture of optimal stand management of Scots pine in a boreal environment with a carbon subsidy system and changing climate.
2. Results on the substantial effect of climate change on optimal stand management, timber yield, and carbon storage.
3. Results suggesting that the optimal adaptation of stand management to changing climate conditions implies significantly higher land values for forest owners, compared to benchmark management.

DISCUSSION

The advantage of complex models

This thesis follows the interdisciplinary approach in stand-level management optimization established in Haight et al. (1985) and Getz and Haight (1989). This approach entails depicting forest growth by detailed ecological models and the simultaneous optimization of initial stand density and thinnings, in addition to rotation age. The simultaneous optimization of all stand management variables enables the determination of genuinely optimal results, without *ad hoc* constraints. It provides results that conflict with earlier results obtained with simpler models or with scenario-based analyses without optimization. The use of a detailed process-based model provides more realistic results than the use of statistical-empirical models, because the former apply causal relationships and feedbacks instead of statistical correlations (Mäkelä et al. 2000). In addition, the use of a process-based model is essential in this thesis for four reasons, as listed below.

1) It enables a very high level of detail in the optimization of thinnings. Statistical-empirical models can be used to optimize thinnings, but that entails the risk of obtaining optimal results outside the sample plot management regimes used to estimate the model. Using whole-stand models and neglecting thinnings in the optimization of Scots pine stand management would be unwarranted and very inaccurate, because thinnings may provide 40% of the overall revenue for Scots pine. All management actions need to be optimized simultaneously and without *ad hoc* constraints. Earlier studies typically apply constraints to the timing, type, number or intensity of thinnings without justifying this with economic terms. Alternatively, previous studies commonly concentrate on using scenarios with fixed management alternatives, thus neglecting optimization. This is particularly pronounced with studies focusing on climate change effects on forest production and management.

2) They enable timber quality consideration, providing very detailed information of the branches that deteriorate timber quality. This information is only available in process-based models, because the statistical-empirical models are incapable of such precision. The importance of timber quality consideration can be seen through the following comparison between study results. Optimal solutions without timber quality consideration report low initial density and no thinnings (Gong 1998), same initial density regardless of interest rate (Hyytiäinen et al. 2005), and the rotation period to shorten with timber price (Johansson and Löfgren 1985; Amacher et al. 2009). These are remarkably different compared to the optimal solutions with timber quality consideration obtained in Study **I**, where the initial density and number of thinnings depend on site conditions and interest rate, and where the doubling of the price of the superior A-grade saw timber may lengthen optimal rotation.

3) They enable studying the carbon pool in a very detailed manner in merchantable timber, branches, foliage, roots, dead trees, and harvest residue, along with timber products. With proper extensions, carbon in soil and fine litter could also be added to the optimization framework. The importance of the extensive carbon pool can be clarified again by the following comparison between study results. Results in Study **II** imply that carbon pricing increases the carbon storage in living biomass, timber products, and dead trees, and that the optimal carbon storage in Scots pine stands is mainly obtained by lengthening the rotation. Niinimäki et al. (2013) use a process-based model for Norway spruce (*Picea abies* (L.) H.

Karst.) and report that optimal carbon storage is obtained by the modification of thinnings. These results with process-based models are in conflict with the results in Pohjola and Valsta (2007), which uses a statistical-empirical model. In their study, the optimal carbon storage in Norway spruce stands is obtained by lengthening the rotation and in Scots pine stands by modifying thinnings.

4) They enable the studying of optimal stand management in a changing climate. Process-based models are able to simulate forest growth in unprecedented climate conditions, whereas statistical-empirical models are only reliable in the conditions of the sample plots used to estimate the model.

Optimal stand management of Scots pine in boreal conditions

The main results of this thesis are the optimal stand management prescriptions that, because of the detail level of the study, may be directly valuable as such in practical management. It is noteworthy how sensitive optimal stand management is to parameter values: solutions are markedly different for various interest rates, growth conditions, and carbon subsidy levels.

First, as a showcase of the importance of the chosen objective and the inclusion of the thinnings, we present the results for an average fertility site. Given the most simple case, volume maximization without thinnings, the optimal rotation is short, 46 years, and the optimal initial density is low, 1500 seedlings. With optimal thinnings, the optimal initial density doubles to 3000 seedlings and the optimal rotation length more than doubles to 96 years. The optimal number of thinnings in this case is five. Bringing in the economic parameters in forest management, i.e. prices for various timber grades, costs, and an interest rate of 3%, drops the optimal rotation to 76 years, the optimal number of thinnings to two, and the optimal initial density to 2000 seedlings.

In Study **I**, the optimal stand management at various sites at various interest rates is determined. General conclusions are that both the optimal initial density and the number of thinnings increase with enhancing growth conditions and decrease with interest rate. The optimal rotation age, in turn, decreases with both interest rate and enhancing growth conditions. However, this latter effect is less clear at high interest rates, where bare land value becomes negative and the optimal number of thinnings becomes zero at poor growth conditions, shortening the optimal rotation length. In this case, the average optimal rotation length is 54.5 years at good sites, but surprisingly only 50 years at poor sites. Cases where the optimal rotation is shorter at poor compared to good sites have not been reported in earlier literature.

All the studies in this thesis provide optimal results for the current climate without carbon subsidies. The results are very similar in all three studies, and the minor differences follow from two model differences. First, the fixed costs are €100 in Study **I**, and €300 in Studies **II** and **III**. Second, Study **II** is the only one to include the possibility of harvesting harvest residues for bioenergy. Increasing the fixed harvesting costs decreases the number of optimal thinnings and the length of the optimal rotation. Inclusion of the possibility for bioenergy harvest tends to decrease the optimal rotation.

Studies **II** and **III** provide optimal results with carbon subsidies in the optimization framework. Compared to Study **III**, Study **II** considers a larger carbon pool (also including the carbon in branches, foliage, harvest residue, and dead trees), along with the possibility of harvesting logging residue for bioenergy. The extent of the framework has rather minor effects on the optimal stand management at good sites, but the difference is remarkable at the two poorest sites. At the poor sites, and when considering results with various carbon prices, the optimal rotation averages 14 years longer with the framework with a more extensive carbon pool and bioenergy.

The manufacturing of timber products is not possible without production losses, which affect the actual decay rates of saw log and pulpwood products. The optimization in Study **III** takes this into account, whereas these losses were omitted in Study **II**. The carbon storage in timber products was therefore over-estimated in Study **II**. Including production losses in the optimization framework of Study **II** was found to change the optimal results, mainly at a high carbon price and given a net carbon subsidy system. Namely the rotation length, tree mortality, and average carbon storage at stand were found to increase, and average timber output and the discounted carbon storage to decrease. However, this implied no changes to the main conclusions of Study **II**. Notably, the inclusion of production losses only slightly changed the results of Study **II** regarding national forest carbon storage costs and the optimal afforestation.

In all cases, the thinnings are almost solely performed from above. Only the first thinning can be from below in cases with high initial density, to salvage trees that would otherwise die because of self-thinning. High initial density has a positive effect on timber quality, because it discourages early branch growth.

Study **III** provides optimal results in a changing climate. Given zero carbon price, the optimal number of thinnings increases with a changing climate and the optimal rotation length first increases and then decreases. At positive carbon prices the rotation length tends to shorten monotonously.

Policy implications

Until quite recently, Finnish forest policy has been guided by MSY-type thinking (Hyytiäinen and Tahvonen 2001). This can be seen, for example, in the recommendations in the widely used silvicultural guidebook, Tapion Taskukirja (Mielikäinen 2008). Particularly noteworthy is their claim that thinnings shorten the rotation by ca. 20–30 years. The reasoning behind this is that smaller trees are to be removed to give larger trees increased space and nutrients to grow in diameter, to reach the predetermined clearcut-triggering dimensions. These thinnings from below have been the usual practice in Finland and Sweden, and they are aimed to anticipate natural mortality, produce pulp wood, and accelerate the diameter growth of the remaining trees. This reasoning is not supported by this thesis, which instead reports optimal thinnings to be almost solely from above. Furthermore, this thesis reports that thinnings lengthen the rotation by several decades, because trees felled at the clearcut are either understory trees or supporting canopy trees in the beginning of the rotation. This is one example that underlines the importance of simultaneous economic optimization of all the decision variables. Even though it is true that thinning may improve the growth of the remaining trees, this may be overshadowed by other aspects essential in the determination of the economic value of the forest stand.

Another widely held view has been that the poorer the site, the longer the optimal rotation (Äijälä et al. 2014). This holds true also in our results, but only when thinnings are not allowed, or even with optimal thinnings when the discount rate is low or the objective is to maximize the cubic yield of timber. Optimal results at higher discount rates show the optimal number of thinnings to be zero at poor sites, leading to very short optimal rotations. This may be a consequence of a fixed harvesting cost and a low yield in potential thinnings.

New forest legislation took effect in Finland in 2014 (new Act (1085/2013) and Forest Decree (1308/2013)). Two major changes implemented were the removal of minimum values for the average tree diameter of trees in a clearcut or alternatively minimum rotation lengths, and the removal of the restriction for thinning from above (restriction reported in Hyytiäinen and Tahvonen 2001). Also, the silvicultural recommendations provided by the government-funded Forestry Development Centre, Tapio, were updated accordingly (Äijälä et al. 2014).

Results in this thesis (concerning rotations, average tree diameter in clearcuts, and thinnings from above after the first thinning) are fairly well in-line with the new recommendations, given an interest rate of 3%, no carbon subsidy scheme, and a steady current climate. This should come as no surprise, as the earlier version of the model in this thesis (Hyytiäinen et al. 2010) was used in the update work of an earlier version of Tapio's silvicultural recommendations. One remaining discrepancy concerns stand density over the rotation, which is lower in the recommendations than in our optimal results.

The silvicultural recommendations fail to take into account the possibility of carbon subsidy schemes and a changing climate, and their impact on optimal forest management. Our results concerning these issues are therefore especially important in forging a new type of thinking in a world increasingly accentuating climate change mitigation and adaptation. This notion is emphasized by the fact that optimal results with carbon subsidy schemes on one hand, and the optimal results in a changing climate on the other, are significantly different compared to benchmark solutions. For example, the carbon subsidy schemes may bring forth the value of dead trees as a carbon stock, increasing their number in optimal stand management, with positive effects to biodiversity because of the provided habitats (Harmon et al. 1986).

Another policy-relevant result in this thesis is that timber production increases with carbon storage up to a certain point. This is in line with other optimization studies (van Kooten et al. 1995; Pohjola and Valsta 2007), whereas studies without optimization (Liski et al. 2001; Kaipainen et al. 2004) report the contrary. This is another example highlighting the importance of the simultaneous optimization of all stand management variables.

An argument has been raised in Finland that maximizing sustained yield (MSY) would simultaneously maximize the stored carbon in forests (e.g. Kauppi and Mäntyranta 2014). In the light of the results of this thesis, this argument seems unwarranted. First of all, optimal rotation also with carbon subsidies depends on the interest rate. Second, assuming a 3% interest rate, the optimal rotation at all sites becomes longer than the MSY rotation when the value of carbon storage is high enough. Third, the MSY approach takes only merchantable timber into account. As seen in Study **II**, a great importance lies in the carbon pool of dead trees and slowly decaying timber products. Furthermore, the optimization of forest management with carbon subsidies with distinct decay rates for different timber products brings forward the possibility of increasing carbon storage by producing more saw timber used for long-lasting products.

Currently, there is a considerable emphasis in Finland towards energy wood procurement to support the strong “bioeconomy” policy by the Finnish government (Prime Minister's Office 2015). This thesis gives insight into the tradeoff between carbon storage and the energy wood potential of forest harvest residues. Assuming a carbon subsidy system and an interest rate of 3%, our results present a break-even curve for bioenergy production. This curve determines the combinations of carbon and energy wood prices where bioenergy production is feasible. This follows from the fact that harvest residue decays slowly in the forest if it is not collected for bioenergy production. If carbon price is over 3.65 times the energy wood (stumpage) price, it is optimal for the forest owner to keep the harvest residue and waste wood in the forest as a carbon stock, and not release the carbon to the atmosphere, thus reducing her carbon revenues.

Forests have been acknowledged for their potential in climate change mitigation (IPCC 2014, p.101). Our results contribute to the case of boreal Scots pine forests, where we find remarkable potential to increase carbon storage by adapting forest management. Currently in the European Union (EU), forest carbon stocks are not dealt with under the Emission Trading System (ETS), or even in the non-ETS-sector, but in the land-use change and forestry -sector (LULUCF). This sector was excluded from the EU climate policy until June 2016, when the European Commission proposed a regulation requiring EU member states to balance the carbon budget in this sector (European Commission 2016). While the exact formulation of the regulation is still to be seen, this dissertation thesis supports the enhancement of forest sinks as a cost-effective carbon abatement measure.

Study **II** reports a potential of 1.5–5.5 $MtCO_2 \cdot a^{-1}$ of additional carbon storage in Finnish Scots pine stands, obtainable in the marginal cost range of €6$\cdot tCO_2^{-1}$ to €92$\cdot tCO_2^{-1}$. These marginal costs are rather low compared to the non-ETS sector marginal costs of €44$\cdot tCO_2^{-1}$ that were available at the time this paper was written (Ekholm 2010). Furthermore, the marginal costs are low compared to those reported in the meta-analysis by van Kooten et al. (2009), where estimates for forest management adaptation are as high as \$46–\$209 (€34–€155)$\cdot tCO_2^{-1}$. The fact that we find considerable carbon storage occurring at marginal costs as low as €6$\cdot tCO_2^{-1}$, is a result of the simultaneous optimization of all relevant stand management variables using a highly-detailed economic-ecological model. This approach enables highly accurate capturing of the various possibilities for enhancing carbon storage.

The results in Study **II** indicate the significance of the carbon subsidy system type implemented. Whether the carbon in harvested trees is assumed to be released to the atmosphere immediately, according to gradual product decay, or never, has a drastic impact on optimal forest management. The higher the cut in subsidy in the clearcut, the more the clearcut is postponed, leading to longer optimal rotations. Interestingly, at low levels of carbon storage, the choice of carbon subsidy scheme does not appear to have a great impact on the carbon abatement costs. However, full assessment of the impact of the carbon subsidy scheme to optimal forest management and carbon storage costs would necessitate a market-level model, determining the relevant prices endogenously. These results are interesting for all regions that are planning to adopt, or that have already adopted, a carbon subsidy scheme (e.g. New Zealand).

A question of remarkable policy interest is whether forest management adaptation or afforestation is the optimal means of carbon storage in Finland. According to the results in Study **II**, the answer depends on the framework used, i.e. are agricultural subsidies included in the analysis or not. In our calculations we assumed that the agricultural field corresponding to a fertile forest site in southern Finland would be afforested with Scots pine and optimally managed given an interest rate of 3% and a carbon price of €40·tCO_2^{-1} in a carbon subsidy system that takes into account the gradual decay of forest products. At this carbon price, afforestation is optimal if the agricultural land value is below €7300·ha^{-1}. This is a relatively low value, as the median market price of agricultural land in 2012 was between €9900·ha^{-1} and €12 000·ha^{-1} in southern Finland (National Land Survey of Finland 2013). However, these prices include agricultural subsidies. Removing their present value at a 3% interest rate (€17 400·ha^{-1}) from the analysis would revert the conclusion. Caution is required in the application of these results, as a detailed analysis would need to assess the changing marginal value of the agricultural land and the timber price due to changing land allocation.

Policy feasibility is an important issue in carbon subsidy schemes. The cost of the scheme to the regulator is an important aspect. In this thesis, subsidy is paid for all carbon storage, including the portion that would have been realized also without the policy. Because this is expensive, the regulator may want to apply an additionality principle and pay solely for the carbon storage exceeding the benchmark (i.e. the optimal carbon storage at zero carbon price). Using a forest vintage model with endogenous prices and land allocation decisions Tahvonen and Rautiainen (2017) show that applying the additionality principle distorts optimal forest rotation and land allocation. However, they also show how these distortions can be avoided through taxation.

Lintunen et al. (2016) assess the policy feasibility of two different carbon payment schemes. The other is the carbon subsidy scheme also studied in this thesis, where carbon sequestration is rewarded with subsidies that have to be paid back when the carbon is released back to the atmosphere. The other scheme is called *carbon rent policy* and is based on periodic rents paid on forest carbon stocks plus an end payment at the time of harvest, rewarding the contribution to carbon storage in products. Lintunen et al. (2016) show that these two policy schemes yield similar market outcomes under perfect capital markets and rational expectations over carbon prices. Furthermore, they suggest that carbon rent policy could be more easily integrated into an emission trading scheme.

In addition to climate change mitigation, adaptation is also needed. Our results in Study **III** report remarkable gains in the bare land values, when forest management is optimally adapted to changing growth conditions. Optimal adaptation necessitates the full consideration of the transition period towards the new changed climate steady state. In comparison, simple adaptation by adopting optimized stand management in the future steady state would lead to a significantly lesser value of adaptation. Optimal adaptation of stand management in a changing climate also provides significantly higher timber yields and carbon storage compared to no adaptation. The inclusion of carbon subsidies has a remarkable effect on optimal stand management also in the framework of changing growth conditions.

Needs for further research

Further research is needed to relax the assumptions that had to be made in this thesis. Ecological research is encouraged to develop process-based models to include the natural regeneration of new trees, which would remove the obligation to carry out clearcuts. This would enable the use of process-based models in the economic optimization of forest management allowing even-aged and uneven-aged management. This economic approach has been applied with statistical-empirical growth models in Tahvonen (2015), Tahvonen and Rämö (2016), Assmuth and Tahvonen (2017), and Assmuth et al. (2017). Allowing the transition from even-aged to uneven-aged forestry is important in optimization, as it can turn out to be economically optimal, especially with carbon subsidies (Assmuth and Tahvonen 2017; Assmuth et al. 2017). Process-based models would give this approach the potential of assessing the optimal forest management with timber quality effects, detailed carbon pools, and a changing climate.

A significant extension to the model used in this thesis would be the inclusion of carbon in the soil and litter, and possibly in the ground vegetation. This would enable the assessment of the full carbon pool in the forest, and a more accurate determination of the carbon stock increase potential in Scots pine stands. Furthermore, the inclusion of soil effects would be essential when further investigating how energy wood harvesting affects soil carbon dynamics. The feedback effects of the removal of harvest residue to the soil nutrient stock may be such that the future forest growth potential deteriorates. Moreover, the inclusion of biodiversity effects of the harvests would be an interesting addition, and easily incorporated into the model used in this thesis.

Further determination of the details of optimal forest management using a market-level or a general equilibrium model would provide new interesting insight on the effect of endogenously altering prices. Comparing the effect of various carbon subsidy schemes on land allocation between forestry and agriculture would be especially interesting. Another significant contribution would be the optimization of forest management starting from any initial stand state (not only bare land). This would result in highly feasible management recommendations when applied with data on the current age-class distribution of Finnish, Fennoscandian, or European forests.

CONCLUSIONS

Painting an accurate and reliable picture of optimal forest management necessitates the use of an interdisciplinary, economic-ecological optimization framework that enables the simultaneous optimization of all stand management variables. This is accomplished in this thesis, contributing to the literature on optimal forest management regarding wood production, carbon storage, bioenergy, and a changing climate. Results are given for all relevant boreal forest growth conditions in an unprecedented level of detail. Therefore, the results of this thesis can be used in developing forest management recommendations, as has already been the case with results obtained when using the earlier version of the model used in this thesis (Hyytiäinen et al. 2010).

The importance of determining optimal carbon storage (Study **II**) can also be seen at a more conceptual level, as is noted by philosophers of science MacLeod and Nagatsu (2016). They consider Study **II**, which they call “the Pihlainen case”, to illustrate two points. First, externalities can be incorporated to economic optimization models in practice, and not only in principle. This is seen as a feasible bottom-up approach in solving the problem of environmental externalities, which avoids the need to resort to economic paradigm shifts. Second, despite the high level of detail, the interdisciplinary framework used in this study is considered to remain sufficiently simple and clear to enable further extensions to the model.

One of the main contributions of this thesis to the economic literature concerns the methodological development of the adaptation value. We follow the line of research of Guo and Costello (2013), who report the value of adapting forest management prescriptions to be only minor. We confirm their result with a similar framework as used in their study, where thinnings are not allowed. However, with optimized thinnings and initial stand density the value of stand management adaptation is remarkable. This finding has far-reaching consequences when considering the optimal tree species selection in a changing climate (Hanewinkel et al. 2010; Hanewinkel et al. 2012). We note that without the careful stand management optimization for each considered tree species, these predictions over large geographical areas fail to capture the full adaptation potential.

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