Dissertationes Forestales 245

On the economics of continuous cover forestry

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Academic dissertation

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This dissertation examines the economics of continuous cover forestry. The analysis is based on an economic description of continuous cover forestry using empirically estimated growth functions, with both size-structured and individual tree models. The optimization problem is solved in its general dynamic form using gradient-based interior point methods. Sensitivity analyzes are conducted for both the ecological and economical parameters.

The thesis consists of a summary section and four separate studies, in which we solve economically optimal continuous cover forestry in single and mixed species stands. We present results for optimal harvests and stand structure, with and without biodiversity consideration, transition toward the optimal steady state, the effect of interest rate and harvesting cost on stand structure, density and optimal harvest timing, and how the optimal results compare to the limitations found in Finnish and Swedish forest legislation. It is found that harvests typically target the largest trees in the stand. In mixed species stands at more productive sites, species diversity increases with the interest rate, with an optimal steady state being a mixed species forest. Taking biodiversity into account in forest management increases species diversity. The harvest timing and intensity are dependent on both the interest rate and the fixed harvesting cost, and if the initial stand is far from the optimal steady state, the legal limitations are violated at least during the transition period.

Keywords: uneven-aged forestry, optimal harvesting, dynamic optimization, single species stands, mixed species stands, biodiversity

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Janne Rämö
Helsinki, Finland
November 2017

LIST OF ORIGINAL ARTICLES

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

I Rämö, J., Tahvonen, O. (2014). Economics of harvesting uneven-aged forest stands in Fennoscandia. Scandinavian Journal of Forest Research 29(8): 777–792. https://doi.org/10.1080/02827581.2014.982166

II Rämö, J., Tahvonen, O. (2015). Economics of harvesting boreal uneven-aged mixed-species forests. Canadian Journal of Forest Research 45(8): 1102–1112. https://doi.org/10.1139/cjfr-2014-0552

III Rämö, J., Tahvonen, O. (2017). Optimizing the harvest timing in continuous cover forestry. Environmental and Resource Economics, 67(4): 853–868. https://doi.org/10.1007/s10640-016-0008-4

IV Rämö, J., Assmuth, A., Tahvonen, O. (2017). Optimal continuous cover forest management with a lower bound constraint on dead wood. Manuscript.

AUTHOR'S CONTRIBUTION

The research ideas for all the articles were developed jointly with Professor Olli Tahvonen. The author constructed the optimization codes for all of the articles, as well as the optimization algorithm for **III**. The author assumed the main responsibility for making the computations, interpreting the results, and writing the research articles.

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1 INTRODUCTION

1.1 Background and motivation

The analysis of optimal forest management has focused on even-aged management, following Faustmann (1849) and Samuelson (1976). In the Nordic region, this has been regarded as the economically most viable approach in utilizing forest resources, and since the 1930s, forest management in Fennoscandia and Canada has been oriented toward even-aged forestry (Siiskonen 2007, Lundmark et al. 2013, Gauthier et al. 2009). In even-aged forestry, the stand is typically artificially regenerated first, then thinned a number of times, and finally, the rotation ends in a clearcut. In this management regime, the trees are roughly the same age and size.

However, during recent years, the discussion and interest toward forest management alternatives has increased (Wikström 2000, Tahvonen 2009, Axelsson and Angelstam 2011). One of the main alternatives under discussion has been continuous cover forestry, where the stand is never clearcut but instead harvested partially, continuously maintaining the forest cover. This forest management typically relies on natural regeneration, and harvests mainly target the large trees (i.e., thinning from above).

Following the discussion, Finnish forest legislation underwent its largest change in decades at the beginning of 2014, when numerous forest management restrictions prohibiting the continuous cover forestry were removed from the legislation. In addition, the focus of the forest policy is shifting from forestry emphasizing timber production to emphasizing biodiversity and forest owners' economic objectives.

Continuous cover forestry has various benefits over even-aged forestry. Perhaps the most important direct economic benefit is the lack of the large initial investment in artificial regeneration. In addition, having typically a more heterogeneous structure compared to even-aged management, continuous cover forestry may provide higher non-commercial benefits, such as recreational, environmental, and aesthetic (Gamfield et al. 2013).

Although the changes in forest policy have been actively discussed in Canada (Puettmann et al. 2009) and Europe (Tahvonen 2006, Valkeapää and Karppinen 2013, Hanewinkel et al. 2014), the number of studies on the economics of continuous cover forestry remains low, especially in boreal conditions. Studies focusing on the economics of continuous cover mixed species stands, in particular, are few, despite their various additional benefits, such as higher levels of biodiversity (Hunter 1990 p. 40–41) and higher resilience to, e.g., climate change (Noss 2001, Thompson et al. 2009, Field et al. 2014). To fill this gap in research, this thesis aims to provide a new understanding on the economics of continuous cover forests, both in single and mixed species stands.

1.2 Literature review

The seminal paper on the optimization of continuous cover forestry using numerical nonlinear optimization is by Adams and Ek (1974). They apply a two-phase optimization, where they first solve the optimal steady state following the marginal value model by Duerr and Bond (1952), and then the optimal harvests during the fixed length transition period. This simplified approach, however, has its limitations (Haight 1985, Haight et al. 1985, Tahvonen and Viitala 2006). While these simplifications are typical for many following studies, some early studies have been able to optimize the continuous cover forestry in general form (Haight 1985, 1987, Haight et al. 1985, Haight and Getz 1987, Haight and Monserud 1990).

Since then, strong simplifications are typical in studies on the economics of continuous cover forestry, especially omitting the dynamic nature of the problem and applying a static optimization framework. Perhaps the most common simplification is to apply a so-called static Investment Efficient optimization approach, first introduced by Adams (1976), and later applied extensively in various papers (see Table 1), even though this setup includes various problems (see Chapter 3).

Table 1 presents the stand-level optimization papers studying the economics of continuous cover forestry. The list focuses on Europe and North America. It is not intended to be exhaustive, especially when it comes to the static optimization papers, but rather to illustrate trends in the research.

First, most of the studies follow Usher (1966) and apply a size-structured growth model where trees move between size classes of fixed sizes. One alternative is to use an individual tree model, which includes the size of the trees as a dynamic variable. This, however, is computationally significantly more demanding.

Second, harvests typically occur every 15–25 years and target mainly the largest trees. However, most of the papers define the harvesting interval as fixed. According to the few papers that optimize the harvest timing simultaneously with the harvest intensities (Wikström 2000, **III**, Tahvonen and Rämö 2016, Sinha et al. 2017), harvesting interval during the transition period may differ significantly from the interval in the optimal steady state. Thus, applying a fixed harvesting interval yields a distorted description on optimal solution when the initial state is not close to the optimal steady state.

Table 1: Stand-level optimization studies on the economics of continuous cover forestry

Article	Location	Mixed species*	Growth model	Optimization	Harvesting interval
Adams 1976	Wisconsin, USA	No	Size-structured	Static	Fixed
Adams and Ek 1974	Wisconsin, USA	No	Size-structured	Dynamic	Fixed
Bare and Opalach 1987	Idaho, USA	Yes	Size-structured	Static	Fixed
Bayat et al. 2013	Iran (Hyrcania)	No	Size-structured	Static	Fixed
Buongiorno and Michie 1980	Wisconsin, USA	No	Size-structured	Static	Fixed
Buongiorno et al. 1995	France	No	Size-structured	Static	Fixed
Buongiorno et al. 2012	Norway	Yes	Size-structured	Static	Fixed
Chang 1981	USA	No	Biomass	Static	Fixed
Chang and Gadow 2010	USA	No	Biomass	Static	Fixed
Goetz et al. 2011	Spain	No	Size-structured	Dynamic	Fixed
Gove and Fairweather 1992	Wisconsin, USA	No	Size-structured	Static	Fixed
Gove and Ducey 2013	New England, USA	No	Size-structured	Static	Fixed
Haight 1985	Wisconsin, USA	No	Size-structured	Dynamic	Fixed
Haight 1987	Arizona, USA	No	Size-structured	Dynamic	Fixed
Haight et al. 1985	Wisconsin, USA	No	Size-structured	Dynamic	Fixed
Haight and Getz 1987	California, USA	Yes	Size-structured	Dynamic	Fixed
Haight and Monserud 1990	Idaho, USA	Yes	Size-structured	Dynamic	Fixed
Liang et al. 2005	California, USA	Yes	Size-structured	Static	Fixed
Parajuli and Chang 2012	Southeast USA	No	Size-structured	Static	Fixed
Pukkala et al. 2010	Finland	No	Size-structured	Static	Fixed
Pukkala et al. 2011a	Finland	No	Size-structured	Static	Fixed
Pukkala et al. 2011b	Finland	No	Size-structured	Static	Fixed
Pukkala et al. 2012	Finland	No	Size-structured	Static	Fixed
Rämö and Tahvonen 2014 (I)	Fennoscandia	No	Size-structured, individual tree	Dynamic	Fixed
Rämö and Tahvonen 2015 (II)	Fennoscandia	Yes	Size-structured	Dynamic	Fixed
Rämö and Tahvonen 2017 (III)	Fennoscandia	No	Size-structured	Dynamic	Variable
Tahvonen 2009	Finland	No	Size-structured	Dynamic	Fixed
Tahvonen 2011	Finland	No	Size-structured, individual tree	Dynamic	Fixed
Tahvonen et al. 2010	Finland	No	Size-structured	Dynamic	Fixed
Tahvonen and Rämö 2016	Finland	No	Size-structured	Dynamic	Variable
Trasobares and Pukkala 2004	Spain	Yes	Size-structured	Static	Fixed
Sinha et al. 2017	Finland	No	Size-structured	Dynamic	Variable
Wikström 2000	Sweden	No	Size-structured	Dynamic	Variable
Xabadia and Goetz 2010	Spain	No	Size-structured	Dynamic	Fixed

*While some papers do include multiple tree species, in some cases they do not have separate growth functions but are instead grouped together in the growth model

1.3 Objectives of the dissertation

At the general level, the objective of the thesis is to increase the understanding on the economics of continuous cover forestry, both in single and mixed species stands. We apply empirically estimated ecological growth models with the economic description of forest management. This interdisciplinary model coupling methodology (MacLeod and Nagatsu 2016) allows us to study the economically optimal continuous cover forestry in more detail than previously. Specifically, the objectives of different papers are as follows.

In paper **I** we study the economically optimal continuous cover forestry in single species stands. The research question is to apply a growth model, not applied prior, and compare the results to existing results. Additionally, we apply both size structured and individual tree models to see how dependent the results are on the model type. Finally, we extend the analysis to birch and Scots pine, which have not been studied before in the context of continuous cover forestry using an economically sound model structure.

In paper **II** we extend the analysis to mixed species stands including birch, Scots pine, and Norway spruce. The aim is to find how the economically optimal stand structure and species composition depend on ecological and economic parameters. The question has not been studied earlier in the boreal region using dynamic optimization. In addition, we include other broadleaves with no commercial value to understand the consequences if only the commercially valuable tree species are harvested.

In paper **III** we generalize the problem by extending economic analysis and optimization algorithms to solve not only harvest intensities, but also harvest timing. This allows us to study an optimal transition toward the steady state and the dependence of harvest timing on economic parameters. We compare the optimal solutions to Finnish and Swedish forest legislations to see if the legislations are limiting the economically optimal solutions. Only one earlier paper exists (Wikström 2000) which attempts to solve the economically optimal continuous cover forestry with optimized harvest timing, but applies various other constraints.

Paper **IV** extends the analysis to include biodiversity management. We optimize the continuous cover forestry with an additional constraint to maintain a set level of dead wood stock. Trees can be felled not only in commercial harvests, but also in biodiversity fellings, i.e., felled and left in the stand to decay, thus accumulating the dead wood stock. This approach allows us to optimize the continuous cover forestry with biodiversity constraints without setting some arbitrary value to it.

2 MODELS AND METHODS

2.1 Stand-level growth models

In individual tree models, the stand state is described by tree age distribution. In these models, the size of the trees, typically measured with the diameter at the breast height (Getz and Haight 1989 p. 230–239), varies between age classes. In its most general form, tree regeneration, mortality, and growth are functions of the stand stage.

Denote the state of the stand at period t by

$$\mathbf{x}_t = \begin{bmatrix} x_{11t} & x_{12t} & \cdots & x_{1nt} \\ x_{21t} & x_{22t} & \cdots & x_{2nt} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1t} & x_{m2t} & \cdots & x_{mnt} \end{bmatrix},$$

where $x_{ist}, i = 1,2,...m, s = 1,2,...,n, t = 0,1,...$ is the number of trees of species i in stage class s at period t. The natural mortality of species i, at stage class s, at period t, is denoted by $\mu_{is}(\mathbf{x}_t), i = 1,2,...,m, s = 1,2,...,n, t = 0,1,...$, the ingrowth of species i at period t by $\phi_i(\mathbf{x}_t), i = 1,2,...,m, t = 0,1,...$, and the 5-year diameter increment of a tree of species i, in stage class s, at period t by $I_{is}(\mathbf{x}_t), i = 1,2,...,m, s = 1,2,...,n, t = 0,1,...$. The stand development can now be given as:

$$x_{i,1,t+1} = \phi(\mathbf{x}_t) - h_{i1t} \tag{1}$$

$$x_{i,s+1,t+1} = (1 - \mu_{is}(\mathbf{x}_t))x_{ist} - h_{i,s+1,t},\ s = 1,...,n-1 \tag{2}$$

$$\delta_{i,s+1,t+1} = \delta_{ist} + I_{is}(\mathbf{x}_t),\ s = 1,...,n-1 \tag{3}$$

$$x_{is0},\ \delta_{is0},\ \delta_{i1t} \text{ given, } s = 1,...,n \tag{4}$$

$$i = 1,...,m,\ t = 0,1,...\ ,$$

where h_{ist} is the number of harvested trees of species i, in stage class s, at period t, and δ_{st} is the diameter of a stage class s at period t.

With no harvesting, all trees not dying via natural mortality increase in age and move from one age class to the next. Thus, the number of trees in each age class decreases with age, resembling the classical inverted-J structure. However, when the model is applied with economic optimization and harvests are optimized, this does not necessarily hold (**I**, Tahvonen 2011).

As these models require separate variables for both the number of trees and their size in each age class and cohort, applying these in a dynamic optimization requires relatively high computational power. Thus, papers studying the economics of continuous cover forestry applying individual tree models are few (Table 1).

However, we can simplify the model to a size-structured model by representing the size of trees by discrete size classes. By dividing the diameter increment with the width of the size class w (Bollandsås et al. 2008), we obtain the fraction of trees moving to the next size class, i.e.,

$$\beta_{is}(\mathbf{x}_t) = I_{is}(\mathbf{x}_t)/w, \; i = 1,2,...,m, \; s = 1,...,n-1, \; t = 0,1,...$$

The fraction of trees remaining in the same size class is thus given as

$$\gamma_{is}(\mathbf{x}_t) = 1 - \beta_{is}(\mathbf{x}_t) - \mu_{is}(\mathbf{x}_t), \quad i = 1,2,...,\mathrm{m}, s = 1,...,n-1, \; t = 0,1,...$$

With these, the development of the stand can be given as

$$x_{i,1,t+1} = \phi_i(\mathbf{x}_t) + \gamma_{i1}(\mathbf{x}_t)x_{i1t} - h_{i1t} \tag{5}$$
$$x_{i,s+1,t+1} = \beta_{is}(\mathbf{x}_t)x_{ist} + \gamma_{i,s+1}(\mathbf{x}_t)x_{i,s+1,t} - h_{i,s+1,t}, \; s = 1,...,n-2 \tag{6}$$
$$x_{i,n,t+1} = \beta_{i,n-1}(\mathbf{x}_t)x_{i,n-1,t} + x_{int}\left[1 - \mu_{in}(\mathbf{x}_t)\right] - h_{int} \tag{7}$$
$$x_{is0} \text{ given}, \; s = 1,...,n \tag{8}$$
$$i = 1,2,...,m, \; t = 0,1,2... \; .$$

Size-structured transition matrix models include the information on the stand structure (cf. biomass models (Getz and Haight 1989, p. 228)), but as they do not require the size of the trees in each age class as a variable, they are computationally less demanding than individual tree models (Getz and Haight 1989, p. 241). Thus, they are more commonly applied in economic optimization studies (Table 1).

In size-structured models, a portion of trees grows from one size class to another, while some trees remain in the same size class. This, combined with the understory competition, results in a stand structure resembling the classical uneven-aged structure, where the number of trees decreases with the diameter of the size class (**I**, Usher 1966).

To prevent the trees from growing more than one size class, the width of the size class is often set to a level that exceeds the maximum growth of a tree (see e.g., Bollandsås et al. (2008)). This approach, however, may result in some issues, as some of the trees are assumed to grow the width of the size class. As a portion of the trees grows the width of the size class, the overall increase in the stand volume may be higher than what the average growth over all trees would account for (**I**, Tahvonen 2011). Hence, this simplification may overestimate the volume increment slightly, especially when combined with optimization.

The model can also be extended to include various non-monetary values. In **IV** we analyze the economically optimal continuous cover forest management with a constraints on levels of decaying wood that is important to biodiversity. Denoting the annual decay-rate of dead wood in decay class k by φ_k , we can denote the development of the dead wood volume by

$$d_{k,t+1} = d_{kt}(1-\varphi_k)^5 + \sum_{i=1}^{m}\sum_{s=k_{low}}^{k_{high}}\left[\left(x_{ist}\mu_{is}(\mathbf{x}_t) + q_{ist}\right)\sum_{j=1}^{u}v_{isj}\right], \tag{9}$$

where k_{low} and k_{high} are respectively the smallest and largest size classes contributing to the dead wood decay class k, q_{ist} the number of trees of species i felled from size class s at period t to accumulate the dead wood stock, and v_{isj} the volume of a timber assortment j of species i in size class s. By requiring the total amount of dead wood to equal or exceed a specific level at all times, i.e.,

$$\sum_{k=1}^{z} d_{kt} \geq \hat{d} \ \forall t , \tag{10}$$

where z is the total number of decay classes, we can solve the economically optimal continuous cover forest management with a constraint on the level of biodiversity.

2.2 Economic models for continuous cover forestry

The economic approach to optimal forest management is straightforward; optimize the silvicultural activities in such a way that the net present value of revenues over an infinite time horizon is maximized. This approach has been applied in even-aged stands in several different contexts, with only timber production (Faustmann 1849, Martin and Ek 1981, Tahvonen et al. 2013) and with additional benefits outside timber production (Hartman 1976, van Kooten 1995, Pihlainen et al. 2014). The approach to economically optimal continuous cover forestry is at its core the same; starting from any initial stand, optimize the harvests so that the net present value of future revenues is maximized (Haight 1985).

Managing a (continuous cover) forest is a dynamic problem. Following Haight (1985, 1987), we can solve the optimal continuous cover forestry using dynamic optimization. Given any initial stand, to find the optimal continuous cover forestry, we maximize the net present value of forestry income and solve the optimal transition and steady state simultaneously. This dynamic approach limits neither the length of the transition period toward the optimal steady state (cf. Haight 1987) nor the steady state stand structure.

By denoting the price of timber assortment j of species i with p_{ij}, and the discount factor with $b = 1/(1+r)$, the objective function becomes

$$\max_{\{g_t, h_{ist}\}} \sum_{t=0}^{\infty} \left(\sum_{i=1}^{m} \sum_{s=1}^{n} \sum_{j=1}^{u} h_{ist} p_{ij} v_{isj} - \sum_{i=1}^{m} C_i\left(\mathbf{h}_t, \mathbf{v}_s\right) - g_t C_f \right) b^{5t} , \tag{11}$$

subject to Eqs. (1)-(3) (or (4)-(8)), where $C_i\left(\mathbf{h}_t, \mathbf{v}_s\right)$ is the harvesting cost function for species i, C_f the fixed harvesting cost, and g_t is the binary vector controlling the harvest timing.

However, a large majority of the economic papers published on the subject of optimal continuous cover forestry apply a static, so called investment efficient optimization approach (Table 1). This approach was first proposed by Adams (1976), and has since been applied in a multitude of papers in different forms (e.g., Buongiorno and Michie 1980, Bare and

Opalach 1987, Buongiorno et al. 1995, Trasobares and Pukkala 2004, Liang et al. 2005, Pukkala et al. 2010, Buongiorno et al. 2012).

According to this approach, the problem is to find harvests over the stand size classes in order to maximize the net present value of all forestry income. This is defined as

$$NPV_T = \frac{N_T}{(1+r)^T - 1} - C_T, \tag{12}$$

where N_T is the net income obtained every T years and C_T is the "value of the initial investment" (Pukkala et al. 2010). The latter is the stumpage value of the stand after harvests, and it is interpreted as the opportunity cost of continuous cover forestry. According to the arguments, this makes the model resemble the Faustmann rotation model. The model has been shown to lack a sound theoretical basis in Haight (1985), Getz and Haight (1989, p.287–295), Tahvonen and Viitala (2006), Tahvonen (2011), and **I**, but it still is applied in recent literature on the economics of continuous cover forestry (see e.g., Schütz et al. 2012).

While this static optimization model has various problems (see **I**), the model is also very restrictive, as it is unable to describe the optimal trajectories toward the continuous cover steady state from various given initial states. Especially transforming an even-aged stand to uneven-aged has attracted interest, and while papers applying optimization remain few, the question has been studied in simulation papers (e.g., Hanewinkel and Pretzsch 2000, Kelty et al. 2003, Nyland 2003, Sterba and Ledermann 2006). Instead, the static approach can only solve the steady state structure, which, applying Eq. (12), is however, correct only accidentally (Haight et al. 1985, **I**). In addition, considering that the transition harvests account for up to 80% of the total net present value of forestry income (**III**), neglecting this in the optimization is clearly restrictive.

2.3 Models and numerical optimization methods

In the four papers of this thesis, we utilize a size-structured transition matrix model, where the model specifies the number of trees for each species in each size class in every period. In addition, in **I**, we also study the more general individual tree model. In all papers, we apply a growth model based on Norwegian national forest inventories, published in Bollandsås et al. (2008).

In paper **I**, we apply growth models for Norway spruce, birch, and Scots pine, in single species stands. In paper **II**, we use same models in a mixed species stand, where we have both intra- and interspecies competition. Additionally, we study how including non-merchantable other broadleaves affect the optimal solution. In paper **III**, we utilize only the growth models for the Norway spruce, but include detailed empirically estimated harvesting cost functions, and focus the analysis on optimal harvest timing. Finally, in **IV** we extend the mixed species analysis to include non-monetary benefits. Table 2 elaborates the characteristics of the optimization models used in the separate studies.

Table 2. Models and data used in the papers of this thesis

	I	II	III	IV
Growth model				
Size-structured	x	x	x	x
Individual tree model	x			
Single species	x		x	
Mixed species		x		x
Species				
Norway spruce	x	x	x	x
Scots pine	x	x		
Birch	x	x		x
Other broadleaves		x		x
Timber pricing				
Stumpage	x	x		
Roadside			x	x
Explicit harvesting costs			x	x
Harvesting interval				
Fixed	x	x		x
Optimized			x	
Non-monetary values				
Biodiversity				x

For **I** and **II**, we use stumpage prices calculated using the average from Finnish stumpage prices from time series 2000–2011 at the level of 2011. For **III**, we use roadside prices and include a detailed harvesting cost function based on work productivity equations in Nurminen et al. (2006) and modified for continuous cover forestry following Surakka and Siren (2007). To be able to optimize the harvest timing in **III**, we also include fixed harvesting costs.

Papers **II** and **III** extend from **I** but in separate directions. **II** applies a similar economic analysis as **I**, but it extends the ecological model to mixed species stands, including interspecies competition. On the other hand, **III** applies a similar ecological model as **I**, but it extends the economic analysis significantly by solving the optimal harvest timing problem for single species stands. Finally, **IV** applies a similar ecological model as in **II**, but extends it by introducing non-monetary benefits and biodiversity management.

In all of the papers of this thesis, we maximize the net present value of forestry income using dynamic optimization and Knitro optimization software (Byrd et al. 1999, 2006). In **I**, **II**, and **IV** we use a fixed harvesting interval and solve the optimal harvests for each period. In **III**, however, we include fixed harvesting costs and solve the optimal harvest timing using a bilevel optimization approach (Colson et al. 2007), where we run two optimization algorithms sequentially (Figure 1). This approach allows us to break the large mixed integer non-linear problem into smaller subproblems.

In **III**, harvest timing, which is an integer variable, is solved using a random-restart greedy hill-climbing algorithm (Russell and Norvig 2009), while the harvests are optimized using the Knitro optimization software. The optimization algorithm used to solve the harvest timing is as follows (Figure 1):

1. Randomly generate initial starting timing for the harvests.
2. Optimize the harvests by solving the non-convex optimization problem for the given harvest timing.
3. Choose one harvest timing/steady state interval that has not been declared optimal.
   - 3.1. Change the timing of the harvest by one period.
     - 3.1.1. In the case of steady state interval, lengthen/shorten the interval by one period
   - 3.2. Optimize the harvests by solving the non-convex optimization problem for the given harvest timing.
   - 3.3. Compare the obtained maximized net present value to a previous solution.
     - 3.3.1. If the net present value is higher, choose as a new starting point, reset optimality of all harvest timings, and move to step 3.1.
     - 3.3.2. If the net present value is lower and the other direction has not been tested, return the previous timing, change direction, and move to step 3.1.
     - 3.3.3. If the net present value is lower and both directions have been tested, declare the timing of the harvest as optimal, and move to step 3.
4. If all harvest timings have been declared as optimal, stop adjusting harvests.
5. Compare the objective of the optimized harvest timings to the previous best solution.
   - 5.1. If the objective is higher, set it as the new best solution.
   - 5.2. If the objective is lower, discard the new solution.
6. Check if the runtime has reached the end threshold.
   - 6.1. If not, move to step 1.
   - 6.2. If yes, end optimization and return the best solution.

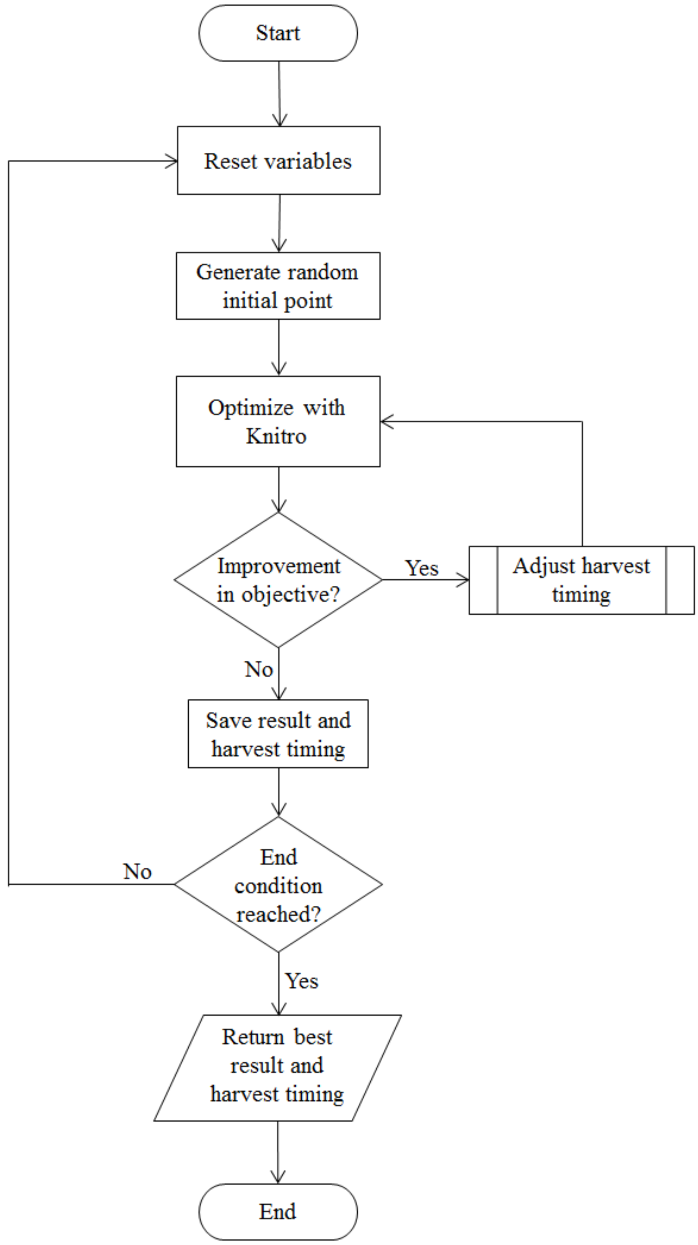

Figure 1: A bilevel optimization approach applied in **III**. Adjusting harvest timing explained in more detail above.

3 RESULTS

3.1 Economics of harvesting uneven-aged forest stands in Fennoscandia (I)

The significance of the applied ecological model type to the results is well known in even-aged forestry (Hyytiäinen et al. 2004). However, in boreal continuous cover forestry research, only a few different growth models have been applied in optimization. Thus, in paper **I**, the research question is to see how dependent the existing results are on the ecological model by applying a model that has not been applied earlier in dynamic optimization.

In paper **I** we apply a fixed harvesting interval in single species stands, consisting of Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.), or birch (*Betula pendula* Roth. and *B. pubescens* Ehrh.). We apply a size-structured transition matrix model and an individual tree model with empirically estimated growth functions presented in Bollandsås et al. (2008). The harvesting interval is fixed to 15 years, and we use species-specific stumpage prices for both sawlog and pulpwood. Prior to this paper, only a few papers on the economics of continuous cover forestry in boreal forests applying dynamic optimization have been published. The lack of earlier research of this kind is especially pronounced regarding the Scots pine and birch.

Assuming no artificial regeneration, we find that the volume yield is maximized by uneven-aged, rather than even-aged management. The economically optimal solution with 3% interest rate produces an average annual yield of 1.9, 6.2, and 3.1 cubic meters (m^3) for Scots pine, Norway spruce, and birch, respectively. Additionally, we find that increasing the complexity of the growth model by applying an individual tree model results in significantly lower yields compared to size-structured model, suggesting that the model type has a more remarkable effect than earlier studies suggest.

Finally, we study the so-called “Investment Efficient” model, first introduced by Adams (1976), and show that in addition to having various theoretical problems (Haight 1985, Tahvonen and Viitala 2006, Tahvonen 2011), the results obtained using this model differ from those obtained using dynamic optimization.

3.2 Economics of harvesting boreal uneven-aged mixed-species forests (II)

In paper **II** we apply the same economic description of continuous cover forestry as in paper **I**, but extend the ecological aspects by studying mixed species stands consisting of all three tree species, with both intra- and interspecies competition. We utilize the same empirically estimated growth functions (Bollandsås et al. 2008), and a size-structured transition matrix model. We show that the optimal steady state is independent of the initial state of the stand. In addition, we show how the changes in site conditions and interest rate changes the optimal steady state.

Only two studies (Haight and Getz 1987, Haight and Monserud 1990) have attempted to solve the complicated numerical optimization problem in the continuous cover mixed-species stands in a more general form. As far as we know, this paper is the first study using dynamic optimization to find the optimal harvesting of continuous cover mixed species stands in Fennoscandian boreal forests.

In our results, maximizing volume yield results in nearly pure Norway spruce stands, with the total yield exceeding that of single species stands presented in paper **I**. When maximizing the net present value of forestry income, increasing the interest rate decreases the total stand density. In less productive sites, the stands are nearly pure Norway spruce stands with all interest rates. However, at more productive sites increasing the interest rate increases the species diversity, with birch accounting for 25–50% of the optimal steady state density.

Finally, we include other broadleaves in the model and assume them to have some noncommercial, e.g., aesthetic, value to the forest owner, and we do not allow them to be harvested. In this case, regardless of site type and interest rate, the other broadleaves will eventually dominate the stand, suggesting that economically viable forestry requires at least partial harvesting of these trees, whether they have commercial value or not.

3.3 Optimizing the harvest timing in continuous cover forestry (III)

In paper **III**, we maintain the ecological model of paper **I** in pure Norway spruce stands but extend the economic analysis by detailed empirically estimated variable harvesting cost functions. In addition, we include fixed harvesting costs and extend the optimization by using bilevel optimization and solving not only the harvesting intensities, but also the harvest timing. This approach has not been systematically applied in the economics of forest resources. We solve the optimal harvests and harvest timing for different levels of fixed harvesting costs and interest rates, as well as for different initial states. In addition, we apply a sensitivity analysis on the timber price.

In our results, increasing the fixed harvesting cost lengthens the harvesting intervals both during the transition period and in steady state, implying heavier harvests. Increasing the interest rate decreases the average steady state density, but it may cause the steady state harvest frequency to decrease or increase due to the flexibility in targeting harvests to different tree size classes.

Optimizing the harvest timing is particularly important when the initial stand state is far from the optimal steady state; during the transition period, the harvesting interval may be 5 times longer compared to the steady state. Most papers studying the economics of continuous cover forestry apply the aforementioned static Investment Efficient model. While this model has various theoretical problems, it also is unable to produce any information on how to converge toward the optimal steady state. This is a significant simplification, as in our results with a 3% interest rate and €300 fixed harvesting cost, the first three transition harvests produce 80–94% of the net present value, depending on the initial state of the stand.

Finally, we show that the legal limitations, both in Finnish and Swedish forest legislation, are constraining the optimal solutions, especially with higher interest rates. Additionally, the higher the fixed harvesting cost, the more the legal limitations are constraining the optimal solutions.

These results are completely new additions to the economics of forest resources. The results emphasize that including flexible harvest timing is necessary for obtaining a theoretically coherent picture on continuous cover forestry and results that make practical sense, especially when the goal is to switch from even-aged to uneven-aged forestry.

3.4 Optimal continuous cover forest management with a lower bound constraint on dead wood (IV)

In **IV**, we extend the analysis to include non-monetary values. The degeneration of biodiversity has been shown to affect human well-being (Diaz et al. 2006, Cardinale et al. 2010), and both the European Union and the United Nations have set various goals to stop the degeneration (European Commission 2011, UNEP 2010). In this paper we aim to see how lower limits on levels of biodiversity affects the economically optimal continuous cover forest management. Specifically, we study how requiring specific amounts of dead wood in the stand affect the optimal steady state structure and species composition, and how large the losses in timber revenues are.

We study mixed species stands with Norway spruce, birch, and other broadleaves, and introduce biodiversity fellings into the model, i.e., harvests with the goal to maintain the dead wood requirement. We combine empirical ecological models for stand growth and wood decomposition with an economic description of continuous cover forest management. This setting produces a coherent picture of optimal continuous cover forestry with dead wood as biodiversity indicator.

Increasing the dead wood volume requirement has only a small effect on the total stand density, but it increases species diversity. In addition, increasing the dead wood requirement has only a minor effect on the total felled amount, but harvests shift from commercial harvests to biodiversity fellings to maintain the required dead wood volume. In the optimal steady state with high levels of dead wood requirement, two harvesting cohorts emerge: one for commercial harvests, and the other for biodiversity fellings. Increasing the dead wood requirement decreases the steady state net timber income by up to 36% compared to an unconstrained solution.

4 DISCUSSION

4.1 Economically optimal continuous cover forest management

Integrating the ecological growth models with the economic description of continuous cover forest management increases the applicability of economic research in policy analysis and forest management planning. However, as has been shown with even-aged models, the results may be very dependent on the economic parameters, as well as on the ecological growth models (Hyytiäinen et al. 2004). Therefore, economic studies on continuous cover management would benefit from further development of growth and yield models.

In all papers of the thesis, optimal harvests target mainly the largest trees of each species. This result follows from the fact that ingrowth is the main limiting factor for stand growth. Additionally, as small trees have no sawlog volume, value growth of the trees is very high especially when the trees first transition to the stage class with sawlog volume. The only exception to this are the results of **IV** with a high dead wood requirement where two harvesting cohorts emerge.

Harvests targeting mainly large trees also result in very high sawlog portions. These results are in line with the existing literature (e.g., Haight and Monserud 1990, Tahvonen et al. 2010, Tahvonen 2011). In single species stands, Norway spruce produces the highest yields and net present value at all sites and with all interest rates. In mixed species stands, with low interest rates, the stand is nearly a pure Norway spruce stand, but species diversity increases with the interest rate. These results follow directly from the distinctive tree species: while Norway spruce is the most shade tolerant of the species studied in this thesis, increasing interest rate decreases the stand density, allowing the less shade tolerant birch to grow at a sufficient rate to be optimal to maintain the stand as a mixed species stand.

In papers **I**, **II**, and **IV** we apply a fixed harvesting interval of 15 years. However, in **III** we extend the economic details to account for explicit fixed and variable harvesting costs. We optimize not only the harvest intensities but also the harvest timing. In our results, the optimal steady state interval varies between 10 and 25 years, depending on the interest rate and fixed harvesting costs. During the transition, however, the time between harvests may be as long as 55 years. Because of this, and the fact that due to discounting most of the net present value is produced by the transition harvests, neglecting the transition harvests by applying a static optimization approach (e.g., Chang 1981, Buongiorno et al. 1995, Pukkala et al. 2010) is a major simplification.

Finally, in **IV** we extend the analysis from only considering monetary benefits of forestry to also take biodiversity into account in the form of dead wood. We show that increasing dead wood requirement increases species diversity. Thus, while we increase the saproxylic habitats, we also gain an increase in the heterogeneity of the stand.

4.2 Policy implications

At the beginning of 2014 the Finnish forest legislation underwent its largest change in decades, with one of the main objectives to make continuous cover forestry a viable option for forest owners. The main limitation for the forest management in the legislation is the lower limit on stand density, under which the forest owner may not go without repercussions (Forest Act 1093/1996 2014). However, studies on the economically optimal continuous cover management in Fennoscandian conditions are few. Hence, there is a clear need for new understanding on the economics of continuous cover forestry.

In **III** we calculate how the economically optimal continuous cover harvests compare to the limitations found in Finnish and Swedish legislation. We find that these limitations are constraining the optimal steady state solutions with interest rates over 3%. In addition, regardless of interest rate, the stand is harvested below these limitations during the transition toward the optimal steady state, especially when the stand was initially far from the optimal steady state. In addition, the higher is the fixed harvesting cost, the more the legislative limitations constrain the solution.

In Finland, the silvicultural recommendations include detailed prescriptions for stand establishment and harvests. After the change in forest legislation, these management recommendations were updated, with additional chapters on the economics and profitability of forest management regimes (Sved and Koistinen 2015), which are partially based on the papers presented in this thesis. Generally, these recommendations are in line with our results (harvests from above), but the recommended harvests are less intense as our results suggest.

5 CONCLUSIONS AND FURTHER RESEARCH

In this thesis, we study the economics of continuous cover forestry, applying dynamic optimization with empirically estimated growth models.

As mentioned earlier, the optimization results may be dependent on the growth model used. Thus, research on the economics of continuous cover forestry applying different ecological growth models would be essential to increase the understanding on the economically optimal continuous cover forestry. Most papers thus far apply a size-structured growth model. The two papers applying an individual tree model (**I**, Tahvonen 2011) report a deviance from the classical, inverted-J structure (Usher 1966); hence studying these models in more detail should be necessary. In addition, extending the ecological aspects to an individual tree (or even process-based) growth models in mixed species stands would give more insight on how dependent the results are on the growth model specifications.

In Tahvonen (2016) and Tahvonen and Rämö (2016) the optimization of forest management is extended to cover both continuous cover forestry and clearcuts, with the choice between these solved endogenously via optimization. Extending this framework to mixed species stands would be interesting and important, as the model would allow a more in-depth analysis on the economics of mixed species forests.

In the all papers of this thesis, we assume the economic and ecological parameters to stay constant over time. In the presence of e.g. climate change this may be quite strong assumption. However, including stochastic variability in timber prices or growth conditions in the already complex model would be very difficult.

Finally, as heterogeneous stands are reported to have a higher resilience to climate change (Noss 2001, Thompson et al. 2009, Field et al. 2014), it would be important to extend the optimization to take into account carbon sequestration and study how the optimal solutions change. Additionally, due to the higher ecosystem services in multispecies stands (Gamfeldt et al. 2013), extending the biodiversity question to allow for the optimization of the choice between clearcuts and continuous cover forestry would produce better understanding of the costs of biodiversity management.

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