Dissertationes Forestales 304

Economics of carbon storage in heterogeneous forests

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Academic dissertation

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public criticism in Room 1, Metsätalo, Unioninkatu 40, Helsinki on 19th November 2020, at 12 o'clock noon.

Title of dissertation: Economics of carbon storage in heterogeneous forests

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Dissertationes Forestales 304

https://doi.org/10.14214/df.304

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ISSN 1795-7389 (online)
ISBN 978-951-651-698-4 (pdf)

ISSN 2323-9220 (print)
ISBN 978-951-651-699-1 (paperback)

Publishers:
Finnish Society of Forest Science
Faculty of Agriculture and Forestry of the University of Helsinki
School of Forest Sciences of the University of Eastern Finland

Editorial Office:
The Finnish Society of Forest Science
Viikinkaari 6, FI-00790 Helsinki, Finland
http://www.dissertationesforestales.fi

Assmuth A. (2020). Economics of carbon storage in heterogeneous forests. Dissertationes Forestales 304. 43 p. https://doi.org/10.14214/df.304

Forests play a vital role in mitigating climate change, as they sequester and store large quantities of carbon. This dissertation examines how carbon storage may be increased by changing forest management at the stand level. To extend the economics of forest carbon storage beyond single-species even-aged stands, this dissertation develops a bioeconomic model framework that incorporates the size and species structure of the stand, and the optimal choice between continuous cover forestry and forestry based on clearcuts. The studies apply empirically estimated growth models for boreal conifer and broadleaf tree species. The dissertation consists of a summary section and three articles.

The first article presents an analytically solvable economic model for timber production and carbon storage with optimized management regime choice between continuous cover and rotation forestry. Continuous-time optimal control theory is utilized to solve the thinning path and the potentially infinite rotation age: if no optimal finite rotation age exists, thinnings are performed indefinitely while maintaining continuous forest cover. The second article extends this model by applying a size-structured growth model for Norway spruce (*Picea abies* (L.) Karst.), road-side pricing of sawlog and pulpwood, variable and fixed harvesting costs, and several carbon pools. The timing and intensity of thinnings, the rotation age, and the management regime are optimized numerically. In the third article, the optimization approach of the second article is extended to mixed-species size-structured stands. Species mixtures include the commercially valuable Norway spruce and birch (*Betula pendula* Roth and *B. pubescens* Ehrh.), and other broadleaves (e.g. Eurasian aspen, *Populus tremula* L., and maple, *Acer sp*.) that have no market value.

Optimal rotation age is shown to either increase or decrease with carbon price depending on interest rate and the speed of carbon release from harvested wood products. Given empirically realistic assumptions, carbon pricing increases the rotation period and eventually causes a regime shift from rotation management to continuous cover management. Hence, carbon pricing heightens the importance of determining the management regime – continuous cover or rotation forestry – through optimization.

Optimal thinnings are invariably targeted to the largest size classes of each tree species. Carbon pricing postpones thinnings and increases the average size of harvested and standing trees, hence increasing mean stand volume. Without carbon pricing, commercially non-valuable other broadleaves are felled during each harvesting operation. When carbon storage is valued, some of the other broadleaves are retained standing until they are large, thus increasing tree species diversity and deadwood quantity.

The results suggest that moderate carbon price levels increase timber yields, especially of sawlog that may be used for long-lived products. Increasing carbon storage through changes in forest management is shown to be relatively inexpensive, and the marginal abatement cost is the lower, the higher the number of tree species in the stand.

Keywords: carbon sequestration, carbon subsidies, continuous cover forestry, dynamic optimization, Faustmann model, forest economics, multi-species forestry, uneven-aged forestry

ACKNOWLEDGEMENTS

This dissertation could not have been completed without the support of a number of people and institutions.

I am deeply grateful to my thesis supervisor, professor Olli Tahvonen for introducing me to the fascinating world of resource economics. Thank you for the highly competent guidance and outstanding knowledge you have provided over the years, and for your insightful comments that have time and again improved my work. Your interdisciplinary research approach has shaped the way I see science, and I am proud to have been a member of the Economic-Ecological Optimization Group. I would also like to thank my co-supervisor professor Jaana Bäck for valuable comments on the natural science side of my dissertation, as well as for general encouragement.

This dissertation project has been generously funded by the Doctoral Programme in Interdisciplinary Environmental Sciences (DENVI) of the University of Helsinki, which I am grateful for. I also wish to thank the Academy of Finland and The Finnish Society of Forest Science for financial support.

I would like to thank senior researcher Kyle Eyvindson for agreeing to act as my opponent. I also wish to thank the pre-examiners, assistant professor Olli-Pekka Kuusela and professor Jussi Uusivuori, for highly valuable comments and suggestions that led to many improvements in my thesis. I am grateful to the members of my thesis advisory committee, university lecturer Pauli Lappi, professor Markku Ollikainen, and professor Timo Vesala, for taking the time to follow my work and propose new ideas. MSc Stella Thompson proofread my texts with great skill (any remaining mistakes are my own) – thank you! My warm thanks go to the whole faculty staff of Environmental and Resource Economics in Viikki for excellent tuition and a friendly academic atmosphere. I would also like to thank the Department of Forest Sciences for excellent research facilities and memorable Pre-Christmas parties.

One of the best aspects of my thesis project has been working as a part of the EEOPT research group, and I would like to thank all former and current team members for their support. From the youngest age class to the oldest: MSc Samuli Korhonen, MSc Matti Laukkanen, MSc Nico Österberg: thank you for bringing a fresh set of brains into the Lab! MSc Vesa-Pekka Parkatti: thank you for excellent co-authorship and for reliable insights on silviculture; also thanks for your company on various lunches and conference trips. Dr. Janne Rämö: thank you for teaching me programming and for sharing your expertise on continuous cover forestry; extra credits for the introduction to the science of sour beer. Dr. Sampo Pihlainen: thank you for tirelessly commenting all my texts; thank you for making me feel welcome since day one and for being a beacon of friendship and fun thereafter. Dr. Antti-Juhani Pekkarinen: thank you for invaluable advice during the writing of my dissertation summary; thank you for great conversations and for helping me approach the light side of the Force.

I also wish to thank my fellow doctoral students at both the Department of Economics and Management and the Department of Forest Sciences for sharing the joys and sorrows of learning to be a researcher. Special thanks to Dr. Emmi Haltia, Dr. Maija Holma, MSc

Johanna Kangas, Dr. Jaana Korhonen, Dr. Tin-Yu Lai, Dr. Sanna Lötjönen, Dr. Brent Matthies, Dr. Jenni Miettinen, and MSc Tuomo Purola for your support.

My friends beyond the campus have been a constant source of perspective, encouragement and distraction from work-related thoughts. For that, I would like to thank Anna, Katarina and everyone else. I am also fortunate to have a family that has supported me in many ways. I would like to thank my grandparents Juhani, Anni and Sirkka for their affection and my parents Laura and Markus for their love and care and for always fostering my curiosity. Big thanks to Tiina as well. From all my heart, I wish to thank my brother Eero and his whole family: your encouragement and example has allowed me to live a fuller life. Finishing this dissertation has been crucially aided by childcare assistance from my parents, my in-laws Kaarina and Heikki as well as my great-aunt Eila – thank you!

Above all else, I want to thank my own family: our late beloved bordercollie Muuvi, our son Otso, and my husband Sampsa. I struggle to find words for describing the love and joy you bring into my life. I would like to thank Muuvi for 13.5 years of devotion, pawtherapy and outdoors company. Much of my love of forests grew out of our daily walks. My wonderful cub Otso keeps on surprising me with his unique combination of wit, tenderness and mischief. Otso, thank you for giving me a clear purpose in life and a strong motivation to finish work in time! And finally, Sampsa: what would I be without you? Throughout my studies, you have encouraged me and believed in me. Thanks to you, I have dared to challenge myself. It has been a privilege to be able to discuss my research and yours, and more generally to share a curiosity about the world and a hope to improve it through our small actions. Thank you for everything!

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 Assmuth, A., Tahvonen, O. (2018). Optimal carbon storage in even- and uneven-aged forestry. Forest Policy and Economics 87: 93–100. https://doi.org/10.1016/j.forpol.2017.09.004.

II Assmuth, A., Rämö, J., Tahvonen, O. (2018). Economics of size-structured forestry with carbon storage. Canadian Journal of Forest Research 48(1): 11–22. https://doi.org/10.1139/cjfr-2017-0261.

III Assmuth, A., Rämö, J., Tahvonen, O. (2020). Optimal carbon storage in mixed-species size-structured forests. Submitted manuscript.

AUTHOR'S CONTRIBUTION

Author Aino Assmuth was solely responsible for compiling the summary of this thesis. The author planned studies **I**–**III** together with Olli Tahvonen, and was responsible for developing the bioeconomic model frameworks for studies **I**–**III**. The author worked on the computational optimization setup for studies **II** and **III** together with Janne Rämö. The author conducted most of the economic analysis for study **I** and all computations for articles **I**–**III**. The author was mainly responsible for writing articles **I**–**III**.

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1 INTRODUCTION

Climate change poses an immense threat to global biosphere functioning and human well-being. According to current estimates, limiting the global temperature increase to 1.5°C requires that carbon dioxide (CO_2) net emissions are reduced to zero by around 2050 and negative emissions are maintained thereafter (Rogelj et al. 2018). This implies that – along with dramatic emissions reductions within sectors such as energy, industry, transport, construction, and agriculture – removing carbon from the atmosphere will be an essential component of a successful mitigation plan. While carbon capture and storage technologies entail considerable uncertainties in terms of availability, safety, and scale (IPCC 2014), terrestrial ecosystems constitute a natural carbon sink with demonstrated potential for large-scale carbon removal (Griscom et al. 2017; Bastin et al. 2019).

Global annual net carbon emissions from fossil fuels and industry equal 9.4 ± 0.5 Gt C yr^{-1} while net emissions from land use, land-use change, and forestry (LULUCF) equal 1.3 ± 0.7 Gt C yr^{-1} (Le Cuéré et al. 2018). Hence, directly human-induced changes in land vegetation currently constitute a significant source of emissions. On the other hand, roughly 30% of the total anthropogenic emissions are sequestered by the terrestrial sink, likely enhanced by CO_2 and nitrogen (N) fertilization and the effects of climate change (Le Cuéré et al. 2018). Forests are the largest, most biomass-rich terrestrial ecosystem (Pan et al. 2013). Estimates of the global carbon stock in forests vary significantly depending on the used methods and definitions, and range from 861 Gt (Pan et al. 2011) to 1464 Gt (Cao and Woodward 1998). Both of these figures clearly exceed the estimated amount of carbon released by human activities since the Industrial Revolution (Ciais et al. 2013). It is clear that continued large-scale damage to forest ecosystems will have alarming consequences for the climate. Conversely, enhancing carbon storage in forests offers substantial potential for climate change mitigation (Birdsey and Pan 2015; Erb et al. 2018).

Unharvested old-growth forests not only store huge carbon quantities but may also retain their carbon sink activity for hundreds of years (Luyssaert et al. 2008). This underlines the importance of preventing primary forest loss. While controlling deforestation has proved difficult, considerable success in afforestation has been achieved in certain areas, especially China and India (Chen et al. 2019). However, globally increasing demand for agricultural products (Tilman et al. 2011) implies that the opportunity cost of afforestation may become prohibitively large once suitable marginal lands have been afforested. Hence, it is highly important to investigate another way of enhancing forest carbon sinks: by increasing the carbon stored per unit of forestland. Forestry may also contribute to climate change mitigation by transferring carbon into long-lived wood products and by offering substitutes for emissions-intensive materials, but these routes entail considerable uncertainties (Pilli et al. 2015; Soimakallio et al. 2016)

Nine per cent of the global ice-free land surface consists of forests with minimal human use, i.e. intact or primary forests. Forests managed for timber and other uses cover as much as 19% of the ice-free land area, and 2% is covered by plantation forests (IPCC 2019, 1.9). This implies that forest management practices (e.g. harvesting, artificial regeneration) greatly impact global forest carbon stocks. Forests are typically managed to produce timber, but also for non-wood forest products like food plants and as habitats for wild game. Unlike these marketable goods, carbon storage provided by forests is an external benefit and thus not taken into account by forest managers, unless society sets up incentives for doing so.

The aim of this dissertation is to explore how the economically optimal management of a forest stand changes when the value of carbon storage is included in the management decision problem alongside the value of timber. This leads to solutions where forest carbon storage is provided cost-efficiently. While most economic studies on forest carbon storage have looked at afforestation rather than stand-level management choices (e.g. Lubowski et al. 2006), a solid body of research also exists on the stand-level economics of carbon storage. However, this dissertation is the first to tackle the problem in a way that incorporates the whole range of management choices from clearcutting and replanting to thinnings that maintain continuous forest cover, and that considers the internal size and species structure of the forest stand. This makes the method applicable and the results relevant for many, if not most, managed forests.

Perhaps even more importantly, by allowing us to understand carbon storage not only in monoculture planted stands but also in naturally regenerating, multilayered and multi-species forests, the framework presented in this dissertation combines climate change mitigation with the perspectives of climate change adaptation and biodiversity protection. A growing body of ecological literature states that compared to homogeneous stands, diverse and selectively managed forests tend to support more ecosystem services (Gamfeldt et al. 2013; Peura et al. 2018) and be more resilient against numerous threats worsened by climate change: droughts, storms, and pests (Trumbore et al. 2015; Jactel et al. 2017; Anderegg et al. 2018). The economic performance of such forests, when optimally utilized for both timber production and carbon storage, deserves thorough investigation. This dissertation aims to initiate such a study.

1.1 Economics of even- and uneven-aged forest management

A stand is the fundamental subject of forest economics: a relatively homogenous parcel of forestland that is managed as one operational unit. Understanding gained from stand-level analysis is essential when studying forest management at market or global level. The economic optimization of stand management has evolved along two distinct paths.

The even-aged approach dates back to the classic Faustmann (1849) model and its revival by Samuelson (1976), and describes rotation forestry where a stand is artificially regenerated and eventually clearcut. The time period between the regeneration activities and the clearcut is called a rotation period or rotation age. Most studies within this tradition apply whole-stand growth models where stand volume is a function of stand age and rotation age is the sole optimized variable (Amacher et al. 2009). While whole-stand models facilitate obtaining analytical results, they entail strong simplifications regarding both forest ecology and economics. Notably, they are limited to even-aged single-species stands and exclude partial harvesting (i.e. thinning) that may be highly important for the economic performance of forestry. Hence, the even-aged approach has been extended first by including thinnings (Clark 1976: 263–269) and later by including a large number of optimized variables from the number of planted trees to the timing, type, and intensity of thinnings (e.g. Niinimäki et al. 2012). Many of these studies apply growth models based on size classes (e.g. Solberg and Haight 1991) or even individual tree classes (e.g. Hyytiäinen et al. 2004). Such models offer much more detailed and realistic results on optimal management practices, and may be used more confidently for policy recommendations.

The economic utilization of structurally diverse forest stands has attracted scientific interest at least since de Liocourt (1898). This, and several modern studies (beginning from

Adams and Ek (1974)), tackle the issue of optimally managing a stand without clearcutting and artificially regenerating it. By selecting certain trees for harvest, and through the natural regeneration of trees, the stand develops into a multilayered population of trees of various ages and sizes. This forest management regime is called uneven-aged or continuous cover forestry, seems to provide more non-timber benefits (Pukkala et al. 2016), and is likely more resilient against climate change (Chapin et al. 2007) than rotation forestry. While for example Haight (1985) and Haight and Monserud (1990) demonstrate that the continuous cover optimization problem should and can be solved in general dynamic form, most studies resort to simplifying the problem into static form (see Rämö and Tahvonen 2014 for a review). However, describing the optimal transition towards a continuous cover steady state requires a dynamic approach where harvest timing is solved simultaneously with the size and number of harvested trees. Such an approach has been presented in Wikström (2000), Tahvonen and Rämö (2016), and Rämö and Tahvonen (2017). As individual-tree growth models are highly challenging to compute, most continuous cover studies apply size-structured models, an exception being the study by Rämö and Tahvonen (2014). Mixed-species uneven-aged stands have been analysed in e.g. Haight and Getz (1987), Haight and Monserud (1990), Rämö and Tahvonen (2015), and Tahvonen et al. (2019).

Rotation forestry is the dominating management regime in most countries with important forest sectors and is clearly able to supply large timber yields to the forest industry. However, concerns and criticism have been voiced regarding its perceived negative effects on forest biodiversity, water management, and recreational values (Keenan and Kimmins 1993; Puettmann et al. 2012). This has sparked scientific interest in its main alternative, i.e. continuous cover forestry, and in the relative superiority of these two management regimes. However, due to diverging research traditions concerning rotation forestry and continuous cover forestry, economic comparisons between them have involved many confusions, inconsistencies, and *ad-hoc* assumptions (see discussion in Tahvonen and Rämö 2016). Tahvonen (2016) and Tahvonen and Rämö (2016) present a coherent model framework that includes both management regimes and optimizes the choice between them. This dissertation extends that generalized optimization framework to include carbon storage.

1.2 Economics of carbon storage in forest stands

Carbon storage in forests is a classic positive externality that can be internalized using economic instruments. The seminal papers by Plantinga and Birdsey (1994) and van Kooten et al. (1995) study the effects of carbon pricing on optimal rotation age and carbon storage supply, showing that valuing carbon storage leads to longer rotations. These and many following studies (e.g. Hoen and Solberg 1997; Akao 2011; Hoel et al. 2014) apply the even-aged Faustmann framework with a whole-stand growth model, implying that rotation age is the only optimized variable.

A smaller body of research analyses carbon storage using an even-aged model that incorporates thinnings. Such studies include Huang and Kronrad (2006) for loblolly pine (*Pinus taeda* L.), Pohjola and Valsta (2007) for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.), Niinimäki et al. (2013) for Norway spruce, and Pihlainen et al. (2014) for Scots pine, the two latter applying highly detailed process-based growth models. According to these studies, adapting thinnings may be as or even more important for increasing carbon storage than lengthening the rotation period. This implies that the simplest

Faustmann model without thinnings is insufficient for determining the most cost-effective methods of carbon abatement in stand management.

While uneven-aged and mixed-species forests are known to provide high levels of several ecosystem services (Peura et al. 2018) and hold important promise for climate change adaptation (Gauthier et al. 2015), economic research on their potential for carbon storage is extremely scarce. As the existing contributions have been limited to static settings (e.g. Buongiorno et al. 2012), Boscolo and Vincent (2003) and Goetz et al. (2010) seem to be the only previous studies on carbon storage in continuous cover forestry utilizing a dynamic model setup. Boscolo and Vincent (2003) emphasize the role of fixed harvesting costs in efficiently combining timber production and carbon storage in a tropical rainforest setting. The results of Goetz et al. (2010) on uneven-aged Mediterranean Scots pine stands suggest that carbon pricing leads to a notable increase in the number of trees, and that carbon sequestration costs are significantly lower for adapting forest management than for afforestation. Because of the historical separateness of rotation forestry and continuous cover forestry research, research on forest carbon storage using a model that includes both management regimes is lacking. Pukkala et al. (2011) present comparisons of even-aged and uneven-aged management for timber production, carbon storage, and bilberry (*Vaccinium myrtillus* L.) yields, but their model does not incorporate the two regimes as equal options nor does it optimize the choice between them.

In short, current understanding of the economics of carbon storage is almost exclusively limited to single-species even-aged stands, and thus only applies to a small fraction of the world's managed forests. Hence, extending the analysis of carbon storage to a wider range of economic and ecological contexts is clearly needed. Further, the analysis should not assume the superiority of either the rotation regime or the continuous cover regime, but instead determine the applied regime through optimization and examine the effects of carbon storage on this choice.

1.3 Objectives of the dissertation

The main objective of this dissertation is to develop a framework for studying forest carbon storage in a generalized setting that incorporates both the continuous cover regime and the rotation regime as well as ecological heterogeneity within the stand. The specific objectives of the studies in this thesis are:

Study **I**

- to develop a generalized model for analysing optimal carbon storage in both even- and uneven-aged forestry
- to obtain analytical results on the effects of carbon pricing on optimal thinning, optimal rotation age, and optimal management regime
- to analyse the role of interest rate and assumptions on carbon release from harvested wood in the optimal co-production of timber and carbon storage

Study **II**

- to develop a detailed, empirically-based numerical model of carbon storage and timber production in size-structured boreal stands that may be managed by applying either continuous cover or rotation forestry
- to develop a description of carbon pools in living trees, dead tree matter, and in harvested wood products, with distinct decay rates for sawlog and pulpwood

- to study the effects of carbon pricing on the timing and intensity of thinnings, and on the rotation age and choice between clearcutting and continuous cover forestry, when the model includes fixed and variable harvesting costs
- to present results on yields, revenues, and the extent of carbon stocks in optimal solutions
- to present marginal costs of carbon abatement *via* increasing carbon storage at the stand level

Study **III**

- to extend the study of optimal carbon storage to mixed-species size-structured stands, with species-specific road-side pricing where certain tree species have no commercial value
- to study the effects of carbon pricing on the timing of harvests along with the size and species of harvested trees and the species composition of the stand
- to present species-specific yield results and to compare timber and carbon revenues under various species mixtures
- to present marginal costs of increasing carbon storage under various species mixtures.

2 MODELS AND METHODS

This chapter lays out the models and methods used in the dissertation. The core of the dissertation is a bioeconomic model framework, where the combined net benefits of timber production and carbon storage are maximized over an infinite time horizon subject to a specific stand growth model. All three articles in this dissertation are variations of this same approach: by concentrating on certain aspects of the model framework and by simplifying others, the articles tackle questions of management regime (**I**, **II** and **III**), carbon pools and size structure (**II** and **III**), and species structure (**III**) in forest stands.

Certain elements are needed to write the bioeconomic model in its simplified, generalized form. Let $\mathbf{x}_t$ denote stand state at the beginning of period t and $\mathbf{h}_t$ harvesting at the end of period t. Let Δ denote the length (in years) of each period. Additionally, let $b = 1/(1+r)$ denote the discount factor, where r is the annual interest rate. Assume that the stand is artificially regenerated at $t = 0$ with regeneration cost w. A finite rotation period implies that the stand is clearcut and then immediately regenerated artificially at the end of period T. Net revenues from harvesting are denoted by $\tilde{R}(\mathbf{h}_t)$, and the economic value of net carbon sequestration in period t, included through a social price of carbon, is denoted by $Q(\mathbf{x}_t, \mathbf{h}_t)$. Following Faustmann (1849), we can utilize the formula of the sum of a geometric series to write the infinite series of identical rotations in compact form. Hence, the optimization problem of maximizing the net revenues from the use of the forest resource becomes

$$\max_{\{\mathbf{h}_t,\, T\in[t_1,\infty)\}} J = \frac{-w + \sum_{t=0}^{T} \left[\tilde{R}(\mathbf{h}_t) + Q(\mathbf{x}_t, \mathbf{h}_t)\right] b^{\Delta(t+1)}}{1 - b^{\Delta(T+1)}} \tag{1}$$

subject to

$$\mathbf{x}_{t+1} = G(\mathbf{x}_t, \mathbf{h}_t), \tag{2}$$

$$\mathbf{h}_t \geq 0,\ \mathbf{x}_t \geq 0, \tag{3}$$

$$\mathbf{x}_{t_1} \text{ given}, \tag{4}$$

for $t = t_1, t_1 + 1, ..., T$, where G is a function describing stand development.

Depending on the model specification, there may be a delay period t_1 during which the planted saplings grow into small trees. Even after this, it may not be optimal to begin thinning immediately. The optimized variables are harvesting $\mathbf{h}_t$, $t = t_1, t_1 + 1, ..., T$ and the rotation period $T \in [t_1, \infty)$. The central feature of this model framework – and the feature that sets this dissertation apart from previous research on forest carbon storage – is that the rotation period may be infinitely long, in which case the stand is never clearcut. This implies that partial harvests are performed indefinitely, maintaining continuous forest cover.

The potential of continuous cover management depends on a sufficient number of new trees emerging into the stand *via* natural regeneration. Even if the stand is eventually clearcut, the optimal utilization of natural regeneration may significantly contribute to the economic performance of the stand. In this dissertation, stand growth is described in a way that is consistent with modern population ecology: individuals emerge, grow, and mature, and finally either die or are harvested (Caswell 2001). Importantly, all of these processes are dependent on the population state. Let us denote the number of trees of species *i* in size class *s*, at the beginning of period *t* by x_{ist}, $i=1,2,...,m,\ \ s=1,2,...,n,\ \ t=t_1,t_1+1,...,T$. The fraction of trees remaining in the same size class in period *t* equals $1-\beta_{is}(\mathbf{x}_t)-\mu_{is}(\mathbf{x}_t)$, where $\beta_{is}(\mathbf{x}_t)$ is the fraction of trees moving to size class $s+1$, with $\beta_n(\mathbf{x}_t)\equiv 0$, and $\mu_{is}(\mathbf{x}_t)$ is natural mortality. Natural regeneration occurs when trees enter the smallest size class: ingrowth at the beginning of period *t* is denoted by $\phi_i(\mathbf{x}_t)$. Additionally, we denote the number of trees harvested from size class *s* at the end of period *t* by h_{ist}. Hence, stand development can be described by the difference equations

$$x_{i,1,t+1}=\phi_i(\mathbf{x}_t)+\left[1-\beta_{i1}(\mathbf{x}_t)-\mu_{i1}(\mathbf{x}_t)\right]x_{i1t}-h_{i1t}, \tag{5}$$

$$x_{i,s+1,t+1}=\beta_{is}(\mathbf{x}_t)x_{ist}+\left[1-\beta_{i,s+1}(\mathbf{x}_t)-\mu_{i,s+1}(\mathbf{x}_t)\right]x_{i,s+1,t}-h_{i,s+1,t}, \tag{6}$$

$$x_{i,n,t+1}=\beta_{i,n-1}(\mathbf{x}_t)x_{i,n-1,t}+\left[1-\mu_{in}(\mathbf{x}_t)\right]x_{int}-h_{int}, \tag{7}$$

where $i=1,2,...,m,\ \ s=1,2,...,n,\ \ t=t_1,t_1+1,...,T$.
This transition matrix model is represented in visual form in Figure 1.

In this dissertation, carbon storage is seen as a positive externality provided by forests. Hence, we can envision a Pigouvian carbon subsidy scheme where sequestering (releasing) carbon is subsidized (taxed). The economic value of one CO_2 unit is denoted by $p_c\geq 0$ and assumed to be constant over time. The amount of CO_2 per one unit of wood can be, in the most simplified specification, denoted by $\mu>0$. The time profile of CO_2 release from harvested trees depends on their eventual use (e.g. bioenergy *vs.* long-lived constructions), and can be captured by an annual decay rate g_j for harvested wood of assortment *j*, with *l* timber assortments. Per unit of harvested wood (see Appendix of article **I**), the present value of future emissions due to decay equals $p_c\,\mu\alpha_j(r)$, where

$$\alpha_j(r)=\frac{g_j}{g_j+r},\ \ j=1,...,l. \tag{8}$$

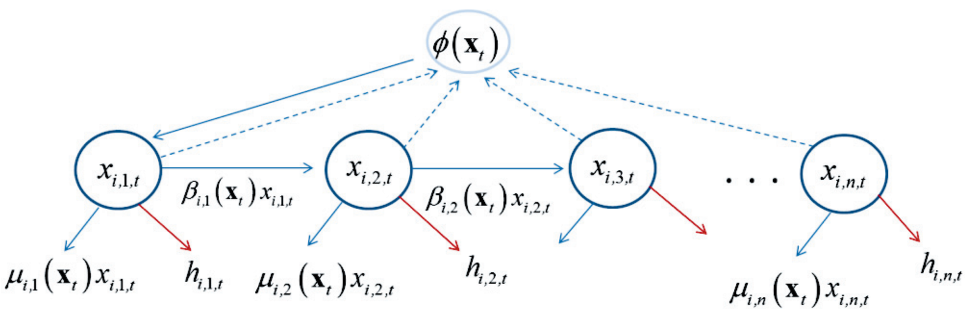

Figure 1. The transition matrix model describing the development of stand structure.

Thus the economic value of net carbon sequestration (or net negative emissions) in period t can be written as

$$Q_t = p_c \mu \left\{ \omega(\mathbf{x}_{t+1}) - \omega(\mathbf{x}_t) + \sum_{j=1}^{l} \left[1 - \alpha_j(r) \right] y_j(\mathbf{h}_t) \right\}, \tag{9}$$

where ω_t denotes stand volume and $y_{j,t}$ is the yield of assortment j, with l timber assortments.

In what follows, I will present the models used in the individual articles of the thesis. Note that the mathematical notation in article **I** somewhat differs from that in the other articles.

2.1 Continuous-time model with endogenous management regimes (I)

In article **I**, we let $\Delta \rightarrow 0$ and the model becomes a continuous-time model. As our aim is to attain analytical results, the net revenue function is simplified by excluding fixed harvesting costs and using stumpage pricing (denoted by p) where variable harvesting costs per m^3 have been deducted from the roadside price. Furthermore, the growth model is a stylized version of the one presented above. We denote stand volume (m^3 ha^{-1}) by $x(t)$ and the rate of harvested volume in thinning (m^3 a^{-1} ha^{-1}) by $h(t)$. Stand volume development is a product of ageing, $g(t)$ and density-dependent growth, $f(x)$:

$$\dot{x} = g(t) f(x(t)) - h(t), \quad x(t_0) = x_o, \tag{10}$$

where x_o is the initial stand volume and $t_0 = 0$ is the moment just after a clearcut. Unlike Clark (1976: 264), we assume that new saplings may emerge into the stand without planting (i.e. through natural regeneration), and thus density-dependent growth may occur even as the stand ages. Hence, we assume that $g(t) f(x)$ may remain strictly positive as $t \rightarrow \infty$. Furthermore, we assume that the ageing function g and the growth function f are continuous and twice differentiable and

$$f(0) \geq 0, \ f(\underline{x}) = 0, \ f''(x) < 0, \ f'(\hat{x}) = 0, \ 0 < \hat{x} < \underline{x}, \tag{A1}$$

$$g(0) > 0, \ g'(t) < 0, \ g''(t) > 0, \ \lim_{t \rightarrow \infty} g(t) = \tilde{g} > 0, \tag{A2}$$

$$\tilde{g} f'(0) > \delta, \tag{A3}$$

where $\underline{x}$ denotes the carrying capacity of the site, $\hat{x}$ is the growth-maximizing stand volume, and δ is the annual interest rate.

Carbon sequestration is determined by stand growth and harvesting, taking into account that carbon may or may not be instantly released from harvested wood. The instant oxidization assumption (applied e.g. in the New Zealand emissions trading system, see Adams and Turner (2012)) implies that $\alpha = 1$, while permanent carbon storage in wood products would allow the assumption $\alpha = 0$. If CO_2 is gradually released from wood products as they decompose, we set $0 < \alpha < 1$.

The optimization problem can now be written as

$$\max_{\{h(t),T,x(T)\geq 0\}} V = \frac{-w+\int_0^T e^{-\delta t}\left[\left(p-p_c\mu\alpha\right)h(t)+p_c\mu g(t)f\left(x(t)\right)\right]dt+e^{-\delta T}\left[\left(p-p_c\mu\alpha\right)x(T)\right]}{1-e^{-\delta T}} \quad (11)$$

subject to (10) and

$$h\in\left[0,h_{max}\right], \quad (12)$$

and where $T\in[0,\infty)$. The integral term in (11) describes the carbon storage revenues and the thinning revenues net of the value of released carbon. Choosing a finite rotation period implies a clearcut and even-aged forestry, while infinite rotation allows maintaining continuous forest cover and thinning without clearcutting.

To present empirical examples, we apply the following growth function specification calibrated using the ecological model in Bollandsås et al. (2008):

$$g(t)f[x(t)]=\left(\frac{1.6}{1+0.04t^{1.2}}+1\right)0.065[x(t)+8]\left[1-\frac{x(t)+8}{378}\right],\ x_0=0\ . \quad (13)$$

The specification describes the growth of Norway spruce at an average productivity site in central Finland.

2.2 Size-structured model with endogenous management regimes (II)

In the second article, we utilize the size-structured transition matrix model given by (5)–(7) in a single-species setting. The initial stand, t_1 periods (or $t_1\Delta$ years) after artificial regeneration, is composed of a given number of trees in the smallest size class. The harvesting revenues per period are specified as

$$R\left(\mathbf{h}_t\right)=\sum_{s=1}^{n}h_{st}\left(v_{\sigma,s}p_\sigma+v_{\varpi,s}p_\varpi\right),\ t=t_1,t_1+1,...T, \quad (14)$$

where $v_{\sigma,s}$ and $v_{\varpi,s}$ are the sawlog and pulpwood volumes in a tree of size class *s*, and p_σ and p_ϖ are the respective (roadside) prices (€ m^{-3}). Variable harvesting costs (for cutting and hauling) are given separately for thinning and clearcuts by $C_u\left(\mathbf{h}_t\right),\ u=th,cl$, as harvesting is somewhat more time-consuming in thinnings than in clearcuts. We include a fixed harvesting cost C_f to cover e.g. planning and the transportation of machinery to the stand site. Due to the fixed cost, harvesting the stand during every period may not be optimal. Hence, we optimize harvest timing along with harvest intensity.

We extend the carbon storage formulation to include whole-tree biomass (and hence harvest residues), dead tree matter, and two separate wood product pools (sawlog and pulpwood). Equation (9) therefore becomes

$$Q_t=p_c\theta\left\{\begin{aligned}&B_{t+1}\left(\mathbf{x}_{t+1}\right)-B_t\left(\mathbf{x}_t\right)\\&+\left[1-\alpha_\sigma(r)\right]y_{\sigma,t}\left(\mathbf{h}_t\right)+\left[1-\alpha_\varpi(r)\right]y_{\varpi,t}\left(\mathbf{h}_t\right)\\&+\left[1-\alpha_d(r)\right]\left(d_{m,t}\left(\mathbf{x}_t\right)+d_{h,t}\left(\mathbf{h}_t\right)\right)\end{aligned}\right\} \quad (15)$$

for $t = t_1, t_1+1, ..., T$, where θ denotes the quantity of CO_2 in one dry mass unit, and $B_{t+1}(\mathbf{x}_{t+1}) - B_t(\mathbf{x}_t)$ refers to net biomass growth. The additional elements $[1-\alpha_\sigma(r)]y_{\sigma,t}(\mathbf{h}_t)$ and $[1-\alpha_\varpi(r)]y_{\varpi,t}(\mathbf{h}_t)$ account for harvested trees that are used for sawlog and pulpwood products, respectively, which release their carbon contents at various speeds. Correspondingly, $[1-\alpha_d(r)](d_{m,t}(\mathbf{x}_t) + d_{h,t}(\mathbf{h}_t))$ refers to dead tree matter (from natural mortality and harvest residues) and its decay.

The problem of optimizing harvests over an infinite horizon can now be given as

$$\max_{\{h_{st}, \delta_t, T \in [t_1, \infty)\}} J(\mathbf{x}_0) = \frac{-w + \sum_{t=0}^{T} Q(\mathbf{x}_t, \mathbf{h}_t) b^{\Delta(t+1)} + \sum_{t=t_1}^{T} \left[R(\mathbf{h}_t) - C_u(\mathbf{h}_t) - \delta_t C_f\right] b^{\Delta(t+1)}}{1 - b^{\Delta(T+1)}} \tag{16}$$

subject to (5), (6), (7), and

$$\delta_t \in \{0,1\},\ t = t_1, t_1+1, ..., T, \tag{17}$$

$$x_{st} \geq 0,\ s = 1,2,...,n,\ t = t_1, t_1+1, ..., T+1, \tag{18}$$

$$h_{st} = \delta_t h_{st} \geq 0,\ s = 1,2,...,n,\ t = t_1, t_1+1, ..., T, \tag{19}$$

$$\mathbf{x}_{T+1} = 0, \tag{20}$$

$$x_{s,t_1} \text{ given.} \tag{21}$$

Restrictions (17) and (19) state that the harvesting level can be positive only if the binary choice of performing or not performing a thinning operation is $\delta_t = 1$. The optimal forest management regime is determined by the choice of *T*. Clearcutting is optimal if – given optimized thinnings – the objective functional is maximized by a finite rotation age. If no maximum exists with finite *T* and the net present value converges toward the continuous cover forestry net present value from below as $T \to \infty$, then it is optimal to apply continuous cover management.

We apply an empirical growth model by Bollandsås et al. (2008) for Norway spruce at an average productivity site, latitude 61.9 ºN. The model includes density-dependent functions for ingrowth, mortality, and diameter increment, and is based on plots from the National Forest Inventory of Norway. Optimization outcomes using the Bollandsås et al. (2008) growth model have been compared to those obtained using a Finnish growth model (Pukkala et al. 2013) in Parkatti et al. (2019). Parkatti et al. (2019) show that the Bollandsås et al. (2008) model is less favourable for continuous cover forestry than the Pukkala et al. (2013) model, mainly because it predicts relatively lower ingrowth. We use 12 size classes with diameters (midpoints) ranging from 7.5 cm to 62.5 cm in 5.0-cm intervals. Each period is five years long, and the time interval from planting to the emergence of trees into the first size class is 20 years. The initial stand structure is given as $\mathbf{x}_0 = [2250, 0, 0, ...]$. The roadside prices for sawlog and pulpwood are €58.44 m^{-3} and €34.07 m^{-3}, respectively, corresponding to average prices in Finland during 2004–2013. The fixed harvesting cost, which may include the cost of transporting machinery to the site as well as planning costs, is set to €500. For the variable harvesting costs we use empirically estimated functions by Nurminen et al. (2006), based on the performance of modern harvesters. The separate cost specifications for thinning and clearcuts take into account that cutting a tree and moving to the next one is more costly in thinning compared to clearcuts, as is hauling. The cost of artificial regeneration equals €1000 ha^{-1}.

2.3 Mixed-species size-structured model with endogenous management regimes (III)

In article **III**, we extend our model to include multiple tree species. As certain tree species may have little to no commercial value, the model allows for felling some trees without hauling them away. The rationale behind such a choice would be to free resources for valuable trees while saving on harvesting costs, as it is more expensive to cut down, pre-process, and haul a tree than to merely cut it down and leave it in the forest. Now, stand development can be described by the difference equations

$$x_{i,1,t+1} = \phi_i(\mathbf{x}_t) + \left[1-\beta_{i1}(\mathbf{x}_t) - \mu_{i1}(\mathbf{x}_t)\right] x_{i1t} - h_{i1t} - f_{i1t}, \tag{22}$$

$$x_{i,s+1,t+1} = \beta_{is}(\mathbf{x}_t) x_{ist} + \left[1-\beta_{i,s+1}(\mathbf{x}_t) - \mu_{i,s+1}(\mathbf{x}_t)\right] x_{i,s+1,t} - h_{i,s+1,t} - f_{i,s+1,t}, \tag{23}$$

$$x_{i,n,t+1} = \beta_{i,n-1}(\mathbf{x}_t) x_{i,n-1,t} + \left[1-\mu_{in}(\mathbf{x}_t)\right] x_{int} - h_{int} - f_{int}, \tag{24}$$

where $i = 1,2,...,m,\ s = 1,2,...,n,\ t = t_1, t_1+1,...,T$, and the second control variable f_{ist} denotes trees felled but left in the forest. In this article, we apply species-specific roadside pricing and extend the empirically estimated harvesting cost functions used in article **II** to include variable felling costs. The sum of variable harvesting and felling costs is defined by $C_u(\mathbf{h}_t, \mathbf{f}_t),\ u = th, cl$, where u stands for thinnings and clearcut, respectively. The fixed harvesting cost is denoted by C. Gross harvesting revenues per period depend on the number, size and species of trees harvested, and are given by

$$R(\mathbf{h}_t) = \sum_{i=1}^{m}\sum_{s=1}^{n}\sum_{k=1}^{2} h_{ist}(v_{isk} p_{ik}),\ t = t_1, t_1+1,...,T. \tag{25}$$

where $k = 1,2$ denotes the timber product assortments of sawlog and pulpwood.

When pricing carbon storage, we modify (9) and (15) by assuming $\alpha_\sigma = \alpha_\varpi = 1$, i.e. carbon storage in harvested wood products is omitted. Hence we denote the present value of future emissions due to deadwood decay simply by α . Additionally, we consider carbon in living and dead stems, but exclude the expansion to whole-tree biomass carried out in article **II**. These simplifications are made to facilitate the computation of a problem with a very high number of control variables. We denote stand volume by ω_t, the deadwood formed through natural mortality by $d_{\mu,t}(\mathbf{x}_t)$, and deadwood created through felling trees by $d_{f,t}(\mathbf{f}_t)$. Hence the economic value of net carbon sequestration in period t can be given as

$$Q_t = p_c \psi \left\{ \omega(\mathbf{x}_{t+1}) - \omega(\mathbf{x}_t) + \left[1-\alpha(r)\right]\left(d_{\mu,t} + d_{f,t}\right)\right\} \tag{26}$$

for $t = 0,1,...,T$, where ψ denotes the quantity of CO_2 in one wood volume unit, $\omega(\mathbf{x}_{t+1}) - \omega(\mathbf{x}_t)$ refers to net volume growth, and $\left[1-\alpha(r)\right]\left(d_{\mu,t} + d_{f,t}\right)$ represents carbon storage in and release from deadwood.

The objective functional (16) can therefore be given as

$$\max_{\left\{h_{ist}, f_{ist}, \delta_t, T \in [t_1, \infty)\right\}} J(\mathbf{x}_0) = \frac{-w + \sum_{t=0}^{T} Q(\mathbf{x}_t, \mathbf{h}_t, \mathbf{f}_t) b^{\Delta(t+1)} + \sum_{t=t_1}^{T} \left[R(\mathbf{h}_t) - C_u(\mathbf{h}_t, \mathbf{f}_t) - \delta_t C\right] b^{\Delta(t+1)}}{1 - b^{\Delta(T+1)}} \tag{27}$$

subject to (22)–(24), (25) and (26), and

$$\delta_t \in \{0,1\}, \tag{28}$$

$$x_{ist} \geq 0,\ i = 1,2,...,m,\ s = 1,2,...,n, \tag{29}$$

$$h_{ist} = \delta_t h_{ist} \geq 0,\ f_{ist} = \delta_t f_{ist} \geq 0,\ i = 1,2,...,m,\ s = 1,2,...,n, \tag{30}$$

$$\mathbf{x}_{T+1} = 0, \tag{31}$$

$$x_{i,s,t_1} \text{ given}, \tag{32}$$

where $t = t_1,\ t_1 + 1, ..., T$.

Our empirical setting approximates a typical Nordic situation where a cohort of an economically preferred native coniferous tree species is artificially established (regeneration cost €1000 ha^{-1}), followed by the natural regeneration of not only this species but also certain economically less-valuable species such as broadleaf trees. We apply the empirical growth model by Bollandsås et al. (2008), latitude 61.9 ºN and average productivity site, for multiple tree species. We assume that at $t = 0$, bare forestland is regenerated by planting Norway spruce. Twenty years after artificial regeneration, 1750 Norway spruce trees emerge in the smallest size class. In addition to the spruce trees, broadleaves may enter the stand through air-borne seeding, originating from nearby forests. We study three different cases: The reference case is a pure Norway spruce stand. In the second case, the initial stand structure consists of 1750 small spruce trees and 1000 small birch trees (silver birch *Betula pendula* Roth and downy birch *B. pubescens* Ehrh.). In the third case, in addition to the 1750 spruce trees and 1000 birch trees, 500 other broadleaf trees – e.g. oak (*Quercus sp.*), maple (*Acer sp.*), European beech (*Fagus sylvatica* L.) and Eurasian aspen (*Populus tremula* L.) – have naturally emerged into the smallest size classes by time t_1.

2.4 Optimization methods and algorithms

In article **I**, we apply continuous-time optimal control theory. Following Clark (1976: 265–269), we first solve optimal thinning while taking the rotation period as fixed, and given optimal thinning we then solve the optimal rotation period *T*. To solve the optimal thinning path, we write the Hamiltonian function and the necessary optimality conditions (Seierstad and Sydsæter 1987: 178–182, theorem 1 and 3) and apply differential calculus. To solve the optimal rotation period, we differentiate (11) w.r.t. to *T*, rearrange, and utilize (10). The numerical examples are computed using Maple software.

Articles **II** and **III** apply numerical optimization. Because the harvest timing variables are integers, but harvest (and felling) intensities are continuous, the task is to solve a mixed-integer nonlinear programming problem. To do this, we apply a bi-level optimization method (Colson et al. 2007). The lower-level problem is computed using versions 9.0 and 10.3 of the Knitro optimization software, which applies advanced gradient-based interior point algorithms (Byrd et al. 2006).

Given any vector of harvest timing binaries, the maximized objective value of the lower-level problem forms the objective value. The harvest timing vector is optimized using a genetic algorithm (Deb and Sinha 2010; Sinha et al. 2017). Optimal harvest schedules are solved for a series of rotation lengths. If the objective function obtains a maximum with some $T \in [60, 180)$ years, the optimal rotation is finite. If the value of the objective function continues to increase as the rotation period is lengthened, the optimal rotation is infinite. In this case, the optimal continuous cover solution is obtained by lengthening the horizon to obtain a close approximation of the infinite horizon solution. To handle potential non-convexities, we apply multiple randomly chosen initial points in the optimization. For the genetic algorithm, we use a randomly generated initial population of 40 harvest timing vectors, and for each harvest intensity optimization we use four random initial points.

3 RESULTS

3.1 Optimal carbon storage in even- and uneven-aged forestry (I)

The first article presents analytical results on optimal thinning and rotation age, as well as stylized numerical examples. Figure 2 shows optimal thinning paths for a set of carbon prices, given a 3% interest rate, a stumpage price of €40 m^{-3}, and $\alpha = 0.7$, reflecting an assumption that half of the carbon content of harvested wood is released back to the atmosphere after 10 years. We show that an initial time interval exists during which harvesting is zero, i.e. the planted stand is initially left to grow undisturbed. Thinning jumps to the optimal path at the moment determined by the necessary optimality conditions (circle symbols in Figure 2). We show analytically that if stumpage price exceeds the value of released CO_2, the rate of thinning exceeds stand growth and stand volume decreases on the optimal thinning path while lying below the growth-maximizing level (e.g. dotted line and short-dashed line in Figure 2). However, if stumpage price is lower than the value of released CO_2, the rate of thinning is lower than stand growth and stand volume increases on the optimal thinning path while lying above the growth-maximizing level (e.g. long-dashed line in Figure 2). Given a positive interest rate, the higher the carbon price, the later thinning begins and the higher the stand density is at any stand age along the thinning path. In Figure 2, given the carbon prices of €0, €25, and €150 tCO_2^{-1}, it is optimal to begin thinning at the stand age of 26 years, 28 years, and 35 years, respectively (and to apply a 109-year, 204-year, and infinite rotation length,

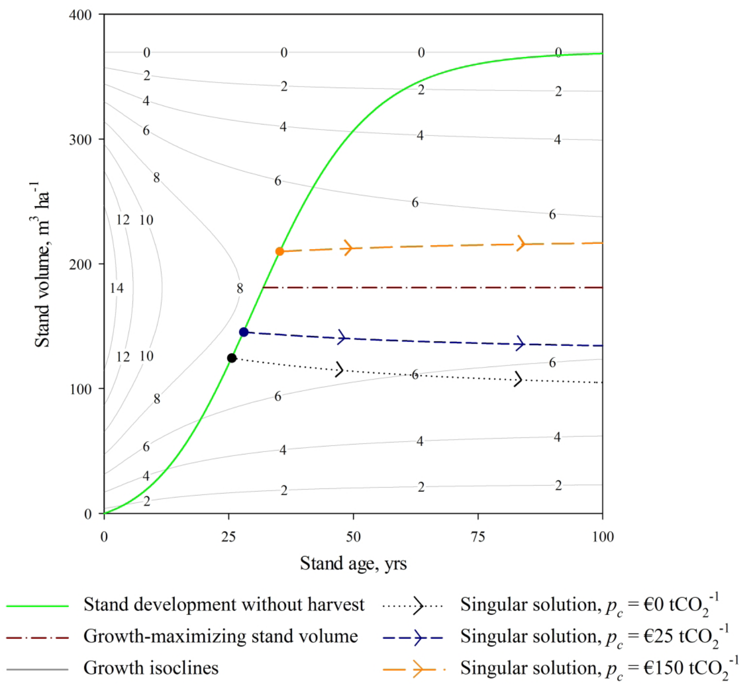

Figure 2. The growth function and singular solutions, with a 3% interest rate and carbon prices €0, €25, and €150 tCO_2^{-1}. Note: p = €40 m^{-3}, $\alpha = 0.7$, w = €1000 ha^{-1}.

respectively). Zero interest rate implies that optimal thinning maintains the stand density at the growth-maximizing level (dash-dotted line in Fig. 2).

Interestingly, if the carbon price is high enough, the shadow value of the forest resource is negative. This implies that the scarce resource is not forest biomass but the remaining capacity for carbon storage. With our numerical specification, such a situation arises with a carbon price of around €60 tCO_2^{-1} when assuming a stumpage price of €40m^{-3} and instant release of CO_2 at harvest.

We show that the optimal rotation period is finite if the long-term yield from thinning is low enough and the sum of clearcut revenues (net of the value of released carbon) and bare land value is positive. Conversely, it is optimal to postpone the clearcut indefinitely if the steady-state carbon storage and wood revenues from thinning exceed the interest earnings for the values of clearcut net revenues and bare land. This is the case if the bare land value is negative, or positive but sufficiently small.

We show that carbon pricing may increase or decrease the optimal rotation age depending on the interest rate and assumptions on carbon release from wood products. More precisely, the optimal rotation period shortens with carbon price if the interest rate is zero and no carbon is released from wood products. However, under more realistic assumptions the rotation period increases with carbon price. In our numerical example with a 3% interest rate, carbon prices in the range of €30–€45 tCO_2^{-1} imply a switch from a finite to an infinite optimal rotation period, i.e. a regime shift from clearcuts to continuous cover forestry (Figure 3).

The main contributions of the study include:

1. Analytical results on optimal thinning with carbon storage.
2. Analytical results on optimal rotation age and management regime choice with carbon storage.
3. Numerical examples of regime shifts between even-aged and uneven-aged forest management.

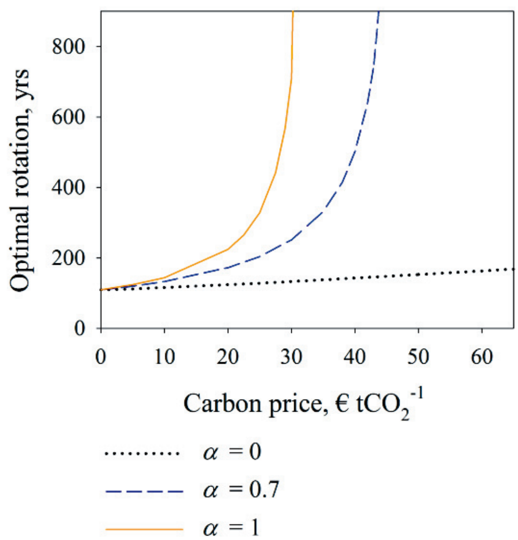

Figure 3. The dependence of optimal rotation on carbon price with different values for carbon release from harvested wood. Note: 3% interest rate, p = €40 m^{-3}, w = €1000 ha^{-1}.

3.2 Economics of size-structured forestry with carbon storage (II)

The results from our empirically detailed model show that optimal rotation age increases with carbon price. Given a 2% annual interest rate, the optimal rotation period becomes infinitely long – implying a switch from rotation forestry to continuous cover forestry – when the carbon price is €30 tCO_2^{-1} or higher (Figure 4). Given a 4% interest rate, continuous cover forestry is superior to clearcutting regardless of carbon price, as a higher interest rate makes it optimal to maintain lower stocking levels and to postpone or avoid the costly investment in artificial regeneration.

Optimal thinning is invariably performed from above, i.e. targets the largest size classes in the stand. With zero carbon price and a 2% (4%) interest rate, the first thinning is carried out at the stand age of 45 (40) years. Carbon pricing postpones thinnings and implies that

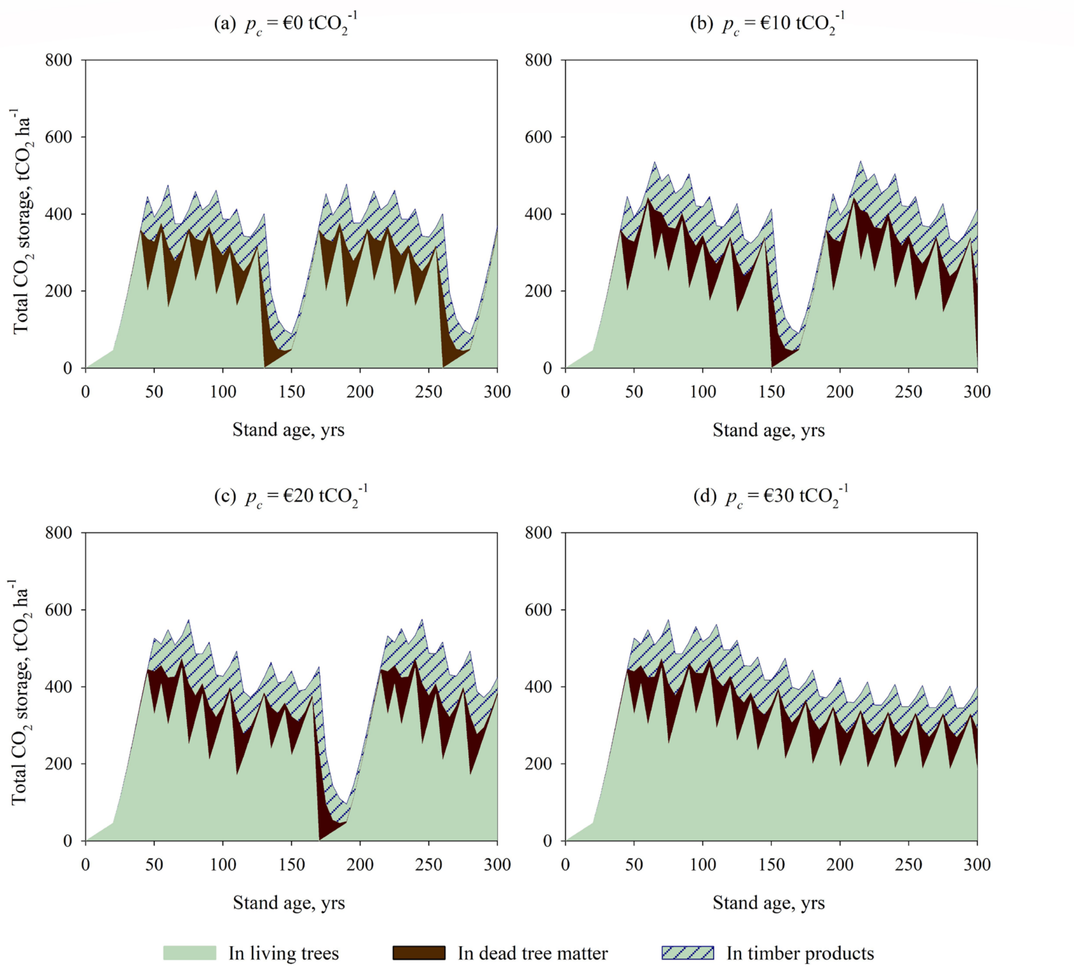

Figure 4. Total carbon storage, including carbon storage in living trees, dead tree matter, and timber products, with a 2% interest rate and carbon prices €0, €10, €20, and €30 tCO_2^{-1}. Note: w = €1000 ha^{-1}.

both the harvested trees and the trees left standing after a harvest are larger. This translates to a higher mean stand volume. At the continuous cover steady states, the thinning interval equals 20 or 25 years, and the diameter of harvested trees ranges from 22.5–37.5 cm to 37.5–57.5 cm, both depending on interest rate and carbon price.

The effect of carbon pricing on yields is not monotone. Moderate carbon prices tend to increase total yields, and sawlog yields in particular, as the sawlog ratio increases with tree size. Yields decrease given a high carbon price – the largest decrease being 21% from the solution with zero carbon price – because only very large trees are harvested. In addition to living trees, carbon is stored in dead tree matter and in timber products.

If the social value of carbon storage is high (€30 or €60 tCO_2^{-1} depending on interest rate), the economic benefits from carbon storage clearly overweigh the income from timber production. Marginal abatement costs with a 2% interest rate range from €3 to €46 tCO_2^{-1} for 10 to 70 tonnes of carbon abatement per hectare, and are somewhat higher with a 4% interest rate.

The main contributions of the study include:

1. A detailed description of timber production and carbon storage for Norway spruce, incorporating the size structure of the stand, multiple carbon pools, and detailed harvesting costs including fixed costs.
2. Results on a comprehensive set of management choices: on the optimal timing, targeting, and intensity of thinnings, and on the optimal rotation age, including the option of applying continuous cover management.
3. Results suggesting that increasing carbon storage through changes in forest management practices is relatively inexpensive.

3.3 Optimal carbon storage in mixed-species size-structured forests (III)

According to the results of article **III**, continuous cover forestry is economically superior to rotation forestry on the studied stand types given a 3% interest rate and a carbon price range of €0–€50 tCO_2^{-1}. Applying thinnings without clearcutting is therefore optimal. The results show that carbon pricing postpones thinnings and increases the mean total stand volume regardless of the stand's species composition. Thinnings are performed from above, fully cutting down the largest 2–5 tree size classes of each tree species (Figure 5).

Norway spruce is the dominating and economically more valuable tree species in the mixed stand containing spruce and birch. A moderate carbon price increases the optimal standing volume of both spruce and birch. With a high carbon price, maintaining high total stand volume is optimal. This negatively affects the growth of the less shade-tolerant birch and implies that the optimal harvesting size of birch is considerably smaller than that of spruce.

In the mixed stand containing Norway spruce, birch, and other broadleaves, without carbon pricing it is once again optimal to maintain a mixture of spruce and birch with spruce comprising the larger share of total volume. To prevent the commercially non-valuable other broadleaves from competing with valuable trees, they are felled and left in the forest during each harvesting operation (Figure 5). With a moderate carbon price, a small number of other broadleaves is left standing after the harvests; with a higher carbon price the volume of other broadleaves is as large as that of birch. Thus carbon pricing incentivizes maintaining other

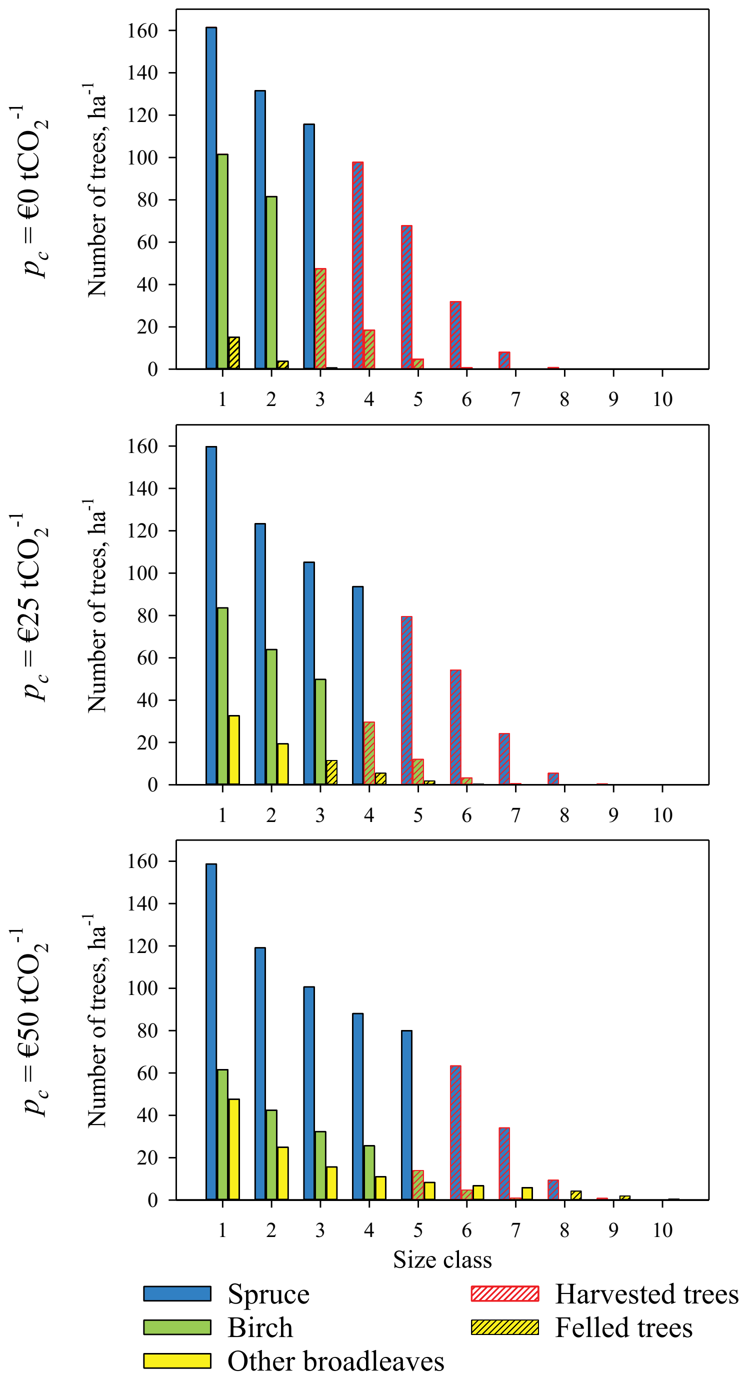

Figure 5. Optimal steady-state structures in stands of Norway spruce, birch, and other broadleaves, with carbon prices €0, €25, and €50 tCO_2^{-1}. Size classes begin from a diameter of 7.5 cm and increase in 5-cm intervals. Note: 3% interest rate.

broadleaves in the forest, as they provide carbon storage and can subsist even in a dense stand. As the other broadleaves are allowed to grow larger before being felled, the deadwood quantity also increases.

Steady-state total yield and spruce yield increase with carbon price. Even without carbon pricing, the naturally emerged birch is a valuable addition to the stand. The presence of other broadleaves is economically disadvantageous if carbon storage is not valued but economically beneficial if the carbon price is high. Finally, a higher number of naturally regenerating tree species at the stand site correlates with a lower marginal cost of increasing carbon storage.

The main contributions of the study include:

1. Economic analysis of carbon storage in mixed-species size-structured stands, a severely understudied forest type with large potential for climate change adaptation.
2. A model for timber production and carbon storage, including fixed harvesting costs along with distinct cost functions for commercial harvesting and for merely felling trees.
3. Results suggesting that tree species diversity may play a role in cost-effective carbon abatement in forestry.

4 DISCUSSION

"It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience." (Einstein 1934.)

In economics, a model is an abstraction of the world, and a good model omits as many things as possible while still being able to capture the fundamental features of the studied phenomenon. Adding complexity to a model should be justified by the need to account for some previously unexplored aspect of the studied question. The simplest Faustmann optimal rotation model is the standard workhorse of modern forest economics, and its carbon storage extension (Plantinga and Birdsey 1994; van Kooten et al. 1995) has spawned a solid body of literature. While most numerical studies utilizing this model find that carbon pricing lengthens the optimal rotation, Akao (2011) and Hoel et al. (2014) study analytically the conditions under which the opposite may also be true. Clearly the advantages of this simple carbon storage setup include its analytical tractability, ease of numerical computations, and compatibility with widely available whole-stand growth models. However, this dissertation argues that the simplest carbon storage model setup lacks two economically and ecologically essential, interconnected aspects: the option of harvesting only part of the stand (potentially indefinitely) and the internal size and species structure of the stand. The approach of this dissertation is to couple ecological models, as constructed by ecologists, with economic optimization models that comprehensively describe the management options and economic incentives faced by a forest owner. Such model coupling is a relatively uncommon but highly effective form of interdisciplinarity in resource economics (MacLeod and Nagatsu 2016) and yields novel results on optimal carbon storage in forests.

4.1 Expanding the optimization framework of forest carbon storage

When carbon storage is studied applying the classic Faustmann model with typical assumptions, a very high carbon price leads to an infinitely long rotation, implying the abandonment of commercial forestry (van Kooten et al. 1995). This dissertation shows that the inclusion of thinnings may dramatically change the implications of an increased rotation length. If natural regeneration is sufficient, stand growth remains positive even in an ageing or old stand, which can be utilized by thinnings even if it is never clearcut. Articles **I** and **II** show that given plausible assumptions, carbon pricing increases the optimal rotation length and eventually leads to a solution where the stand is thinned maintaining continuous forest cover. This result is unprecedented in the carbon storage literature, because previous models that incorporate thinnings (e.g. Huang and Kronrad 2006; Pihlainen et al. 2014) omit natural regeneration and the possibility of applying continuous cover management. Hence, the previous understanding of the effects of carbon pricing on optimal rotations has been severely restricted by a model framework that only includes the even-aged management regime. Conversely, the few previous studies on optimal carbon storage in uneven-aged forestry have not considered the option of clearcutting the stand.

Relaxing the assumptions concerning the management regime obviously comes with the cost of a less tractable optimization model. However, article **I** demonstrates that carbon storage in both even- and uneven-aged forestry can be studied analytically as well as numerically by extending the Clark (1976) model that combines elements of the Schafer (1957) biomass harvesting model with the Faustmann model. As far as I know, article **I** presents the first analytical results on partial harvesting with carbon storage: carbon pricing implies that thinnings are postponed and a higher stocking level is maintained throughout the (potentially infinite) rotation. The analysis is in line with previous numerical studies, but reveals an interesting, previously undiscovered phenomenon. If the carbon price is sufficiently high (yet empirically quite realistic) relative to timber price, the shadow price of the timber resource is negative. In such a case, thinning revenues net of the cost of releasing carbon are negative, but it is still optimal to thin the stand to maintain capacity for carbon sequestration. These results suggest that given high carbon prices, the value of bare forestland may be higher than that of fully stocked forestland, and that even in managed forests the main source of revenues may be carbon storage instead of timber.

4.2 Incorporating size and species structure

While article **I** expands the previous understanding of carbon storage by including thinnings and the option of applying uneven-aged management, it utilizes a very stylized model where the stand is described only in terms of stand age and stand biomass. Additionally, the model omits fixed harvesting costs and hence it is optimal to apply continuous thinning, which is not the case in practical forest management. In article **II**, the internal structure of the stand is included by applying a size-structured growth model of Norway spruce with empirically estimated growth, mortality, and ingrowth functions. Moreover, we include the size class-specific volumes of sawlog and pulpwood in tree stems and the distinct decay profiles of these two timber assortments. This detailed description of forest growth and yield is the basis on which an economically realistic model of forest management is built by including road-side pricing and variable and fixed harvesting costs. While these features add to the complexity of the model and to its computational demands, they are essential for determining viable management prescriptions that can be applied in practice. They are also required for presenting realistic estimations of the costs of increasing carbon storage in forestry.

The results of article **II** show that the average size of the harvested trees (and of the remaining trees, as thinnings are performed from above) in the thinnings increases with carbon price. This increases not only the standing volume but also the share of slowly decaying sawlog of total yields as the sawlog-pulpwood ratio is higher in larger trees. Similar effects have been found in e.g. Pihlainen et al. (2014) using a detailed model with several timber assortments. Moreover, as carbon pricing lengthens the optimal rotation periods and eventually implies a switch to continuous cover management, the share of the pulpwood-heavy clearcut yield of the total yield decreases. This effect is only partially seen using models that are limited to rotation forestry. We find that the incorporation of stand size structure broadens the space of stand-level mitigation options: thinnings may not only be postponed and moderated but also targeted to larger trees, and this along with postponing or avoiding the clearcut increases carbon storage both in the stand and in harvested wood products. This also implies that a whole-stand model that omits stand size structure cannot fully capture the advantages of continuous cover forestry for carbon storage.

Article **III** extends the economics of carbon storage to mixed-species size-structured stands. To account for a range of species mixtures, the study includes two mixed-species scenarios: one with high-value Norway spruce and slightly less valuable birch, and another with spruce, birch, and other broadleaves that have no commercial value. The results imply that carbon storage alters the optimal species composition of a forest stand, and the changes depend on the relative prices and ecological characteristics of the various tree species. Notably, carbon pricing incentivizes postponing the felling of commercially non-valuable tree species, which is a novel result in the literature on forest carbon storage. This finding also suggests that carbon pricing may increase biodiversity *via* increased tree species diversity and deadwood. Based on the marginal costs calculated in this study, the differing profiles of tree species in terms of ecological requirements and economic value seem to offer possibilities for cost-efficient carbon abatement. This complements the ecological literature stating that tree species diversity supports carbon storage (e.g. Ruiz-Benito et al. 2014; Mensah et al. 2016).

4.3 Future research directions

The economic literature on forest carbon storage beyond even-aged single-species management is very scarce. This dissertation sets out to explore the most central aspects of the economics of carbon storage in heterogeneous forest stands. However, many aspects beyond the scope of this dissertation merit further study.

A fundamental, "heroic" (Samuelson 1976) assumption applied in all of the models in this dissertation is that the economic and ecological parameter values remain fixed over an infinite time horizon. I feel this is a well-justified assumption given the previous severe lack in the scientific understanding of the studied phenomena. However, relaxing this assumption opens up various research questions. According to integrated assessment models and other models for determining optimal global emission paths, the social cost of carbon is rising throughout the next century (Nordhaus 2017; Cai and Lontzek 2019). Correspondingly, the European Union (EU) emissions reduction commitments imply that the carbon price within the EU Emissions Trading Scheme may increase to €11–€53 by 2030 and to €85–€264 by 2050 (European Commission 2014, 80–81). Forest carbon storage under increasing carbon prices has been studied in even-aged settings (van't Veld and Plantinga 2005; Ekholm 2016, Rautiainen et al. 2018), and analyzing the implications for regime shifts between even-aged and uneven-aged management would be an interesting next step.

On the other hand, the economics of carbon storage may be studied under changing climate (Sohngen and Mendelsohn 1998). As climate change affects tree species in different ways, planting more suitable tree species may be optimal (Hanewinkel et al. 2010; Guo and Costello 2013). However, the issue has not been analysed in naturally regenerating mixed-species stands, where transitions between species mixtures could be performed gradually and with lower costs.

Further basic assumptions behind the model framework used in this thesis include well-defined property rights, perfect capital markets, and a net revenue-maximizing forest owner. Relaxing either of the two former assumptions would be highly relevant for studying forest carbon storage in the context of developing countries, where open-access situations and borrowing constraints may be common. Within industrialized countries, the forest owner's environmental preferences regarding biodiversity or climate change mitigation may have a significant effect on management decisions and the optimal formulation of policies for increasing forest carbon storage (cf. Koskela and Ollikainen 2001).

The scarcity of suitable empirical growth models is a challenge for building bioeconomic forestry models. For Fennoscandian stands, size-structured growth models that include functions for natural regeneration have been estimated in Norway (Bollandsås et al. 2008) and in Finland (Pukkala et al. 2009, Pukkala et al. 2013). According to Parkatti et al. (2019), the most significant differences between the Bollandsås et al. (2008) and Pukkala et al. (2013) models lie in the ingrowth functions. This is not surprising considering that the emergence of new saplings is a highly stochastic process that is still unsatisfactorily understood. Moreover, the existing growth models do not take into account that larger trees produce more seeds, i.e. the models assume that a sufficient amount of seeds is always produced, which may in reality not be the case if the stand only consists of young and small trees. This potentially problematic feature could be handled in optimization by setting lower bounds on the numbers of large trees. Notwithstanding, the availability of more and improved growth models describing heterogeneous naturally regenerating forests would be highly beneficial for the economic optimization of stand management.

This dissertation analyses the optimal co-production of timber and above-ground carbon storage. In addition to living biomass, deadwood and litter, carbon is also stored in forest soil. The relative size of the soil carbon pool in forests varies between climatic regions: in the tropics, the above-ground carbon pool is significantly larger than the soil carbon pool, while the opposite is true for boreal forests (Pan et al. 2011). However, the effect of forest management activities (assuming no land-use change) on soil carbon stocks may be small and mostly limited to the forest floor layer, in contrast to the relatively stable mineral soil layer (Jandl et al. 2007; Nave et al. 2010). Intensive harvesting, especially clearcutting and whole-tree harvesting, increases the emissions from soil by increasing its surface temperature and by removing the source of litter inflow for a number of years (Lytle and Cronan 1998; Jandl et al. 2007; Achat et al. 2015). This implies that extending the optimization framework presented in this dissertation to include soil carbon would likely increase the competitiveness of continuous cover management relative to clearcuts. A realistic optimization model should also take into account that soil carbon stocks and harvesting effects depend on both tree species and soil type (Nave et al. 2010; Vesterdal et al. 2013). Finally, if the accumulation or degradation of soil carbon is slow and unfolds over several centuries, the classic Faustmann formulation – based on identical rotations – becomes mathematically inadequate.

The albedo effect, i.e. darker surfaces, such as mature forests, reflecting less radiation than open land, especially when snow-covered, is a topic with potential implications for socially optimal forest management. Further, tree species differ in their ability to reflect solar radiation; evergreen conifers typically have lower albedo values than deciduous trees (Anderson et al. 2011). The effects of both carbon storage and albedo on optimal forest management have been studied by e.g. Lutz and Howarth (2014), Matthies and Valsta (2016), and Rautiainen et al. (2018). These studies suggest that including albedo may significantly decrease the rotation period, but these results are sensitive to (species-specific) albedo parameters. Moreover, future research striving to understand the full climate impacts of forests should incorporate not only carbon storage and albedo but also the climate-cooling capacity of volatile organic compounds and aerosols emitted by forests, as these are likely to have opposing effects relative to albedo (Kulmala et al. 2004; Hallquist et al. 2009).

An interesting research avenue would be to study carbon storage alongside other forestry-related externalities, such as nutrient and sediment loads to water bodies. Water protection in boreal even-aged forestry has been studied e.g. in Miettinen (2020). On the other hand, Nieminen et al. (2018) show that compared to even-aged management, continuous cover management may decrease greenhouse gas emissions and negative water quality impacts on drained peatlands used for forestry. Hence the inclusion of both climate and water quality impacts of forestry in an optimization framework that incorporates thinnings and the option of continuous cover management would be an important extension especially relating to peatlands.

4.4 Policy considerations

This dissertation aims to contribute to the theoretical understanding of the economics of forest carbon storage. Additionally, the articles in this thesis present empirically grounded examples of adapting forest management to increase carbon storage. According to the results, lengthening the rotation period is beneficial, but should not be the only measure taken: stocking levels over the rotation should be increased by postponing thinnings and by increasing the size of trees left standing after harvests. Continuous cover forestry seems to offer climate benefits over rotation forestry. Given that structurally diverse stands are also likely to be more resilient against natural disturbances than homogeneous stands (Chapin et al. 2007; Gauthier et al. 2015), mixed-species continuous cover forestry may offer potential for combining climate change mitigation and adaptation. Our results also suggest that plausible future levels of carbon price are sufficient to cause major changes in optimal stand management.

Adapting stand management to account for carbon benefits in addition to timber revenues changes the supply of timber from the stand, which has an effect on timber prices. Painting a complete picture of this dynamics would require a market-level model with endogenous timber prices. A market-level approach would also enable examining how alternative assumptions on after-harvest carbon release are reflected in timber prices, potentially affecting the dependence of optimal rotation age on carbon price in a way that is not captured in this thesis (e.g. comparative statics in Figure 3). However, some initial understanding of supply effects can be obtained from the stand-level models presented in this dissertation. When assuming positive interest rates, moderate carbon pricing increases the timber supply, as it is optimal to maintain a higher stock of growing capital in the forest. Given high carbon prices, only large trees are harvested in continuous cover thinnings, which decreases the timber supply. On the market level this would increase the price of timber, especially of pulpwood, which at the stand level would then incentivize shifting the emphasis of management slightly back towards timber production.

In this dissertation, the carbon storage externality is valued to its full extent. This may be prohibitively expensive in practical policy, as is implied by the large discounted sums of net carbon subsidies (article **II**, Table 5). Hence, policy makers are more likely to device a subsidy system based on carbon storage that is additional to the business-as-usual management solution. According to stand-level analysis, applying the additionality principle leads to identical management solutions, as when subsidies are paid for the whole extent of net sequestration. However, market-level analysis with forest vintages shows that pricing additional storage induces distortions to both rotation age and the allocation between forestland and agricultural land (Tahvonen and Rautiainen 2017). These distortions may be corrected by a lump sum tax on land (Tahvonen and Rautiainen 2017). While most of the literature on the economics of carbon storage is based on the subsidy–taxation approach utilized also in this thesis, an alternative approach called the carbon rental policy has been proposed in some studies (Sohngen and Mendelsohn 2003, Uusivuori and Laturi 2007). However, it is clear that any subsidy scheme for forest carbon storage involves many challenges regarding financing, political acceptability, leakage, verification, and transaction costs (Sedjo and Sohngen 2012). These issues have been salient e.g. in the New Zealand and California forest carbon schemes (Gren et al. 2016).

In international carbon emissions accounting, changes in forest carbon stocks are accounted for in the LULUCF sector and the use of forest biomass is thus exempted from emissions liabilities (Krug 2018). As harvested wood products may also store carbon for significant periods of time, they have been included in the LULUCF inventory. From the economic viewpoint, the first-best policy would be to subsidize (tax) carbon sequestration (release) when and where it occurs. This would imply a policy where forest carbon storage would be subsidized without subtractions for harvested volume (i.e. setting $\alpha = \alpha_{\sigma} = \alpha_{\varpi} = 0$ in articles **I** and **II** of this dissertation), and emission liabilities would be assigned to wood users instead, as in the general equilibrium framework in Tahvonen (1995). While such a system ensures that each economic agent faces the correct incentive to control net emissions, it may be unfeasible in practice. Moreover, such a comprehensive system of pricing forest-based along with fossil-based emissions would likely yield substantially different forestry input and output prices than those seen currently. Hence, this dissertation deploys a second-best approach that is closer to current policies: the forest owner receives subsidies based on stand growth net of harvests, and carbon storage in harvested wood products is either omitted, as in the New Zealand carbon scheme (article **III**), or taken into account using timber product decay rates (articles **I** and **II**).

The congruence of carbon storage and biodiversity objectives has lately become the object of intense scientific attention, as local and global policies are being crafted to limit deforestation and forest degradation, and to support afforestation (Díaz et al. 2009; Strassburg et al. 2010). The results of this thesis suggest that carbon pricing incentivizes adapting forest management in a way that increases the number of large trees and quantity of deadwood, promotes structural diversity inherent to continuous cover forestry, and maintains higher tree species diversity. As these features are likely to be beneficial for the protection of forest biodiversity (McElhinny et al. 2005; Gao et al. 2015), increasing carbon storage in boreal forests seems to have high potential for side benefits.

5 CONCLUSIONS

This dissertation expands the economics of forest carbon storage into a previously unexplored direction: uneven-aged and mixed-species stands. I argue that the classic Faustmann optimal rotation model is an insufficient basis for studying carbon storage, as it is readily applicable to only a fraction of the world's forests. A broader understanding of optimal carbon storage necessitates a model that acknowledges the internal heterogeneity of forest stands and its implications for growth, harvesting, and yields of various timber assortments. To this end, I develop a bioeconomic model framework where the optimal co-production of timber and carbon storage may be studied by optimizing all the relevant management choices, including thinnings and the choice between continuous cover and rotation forestry. The three articles in the thesis consider fundamental theoretical aspects of stand-level forest carbon storage (**I**), empirically realistic management prescriptions for increasing carbon storage in size-structured stands (**II**), and the interaction between optimal carbon storage and tree species structure (**III**).

According to the results, cost-effective methods for enhancing carbon storage include lengthening the rotation period and eventually switching to continuous cover management, where timber revenues can be obtained even when the stand is never clearcut. Further, the results show that pricing carbon implies changes to partial harvests: thinnings are postponed and limited to large trees, and trees of commercially non-valuable species are allowed to remain in the stand. The results demonstrate that while high levels of carbon price may decrease timber yields moderately, carbon pricing typically increases mean timber yields. Finally, the results suggest that stand-level carbon mitigation may be relatively inexpensive and is likely to involve biodiversity co-benefits. The results of this thesis support the notion of setting up economic incentives to increase carbon storage by adapting stand management.

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