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On the economics of continuous cover and rotation forestry

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Academic dissertation

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ABSTRACT

This dissertation studies the stand-level economics of continuous cover and rotation forestry. The main method of this dissertation is economic-ecological optimization, where statistical-empirical size-structured ecological models are coupled with economic optimization models including fully flexible optimization between continuous cover and rotation forestry. The dissertation consists of a summary section and three original research articles. The first article compares the favourability of continuous cover forestry between pure Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) stands and studies the effects of ecological models on economically optimal solutions. The second article studies the economics of mixed-species stands with up to four tree species. The third article studies the economics of arctic forestry in the homeland region of the Sámi people using a model that simultaneously includes timber production, carbon storage, and negative externalities of forestry on reindeer husbandry.

According to the results, the differences in continuous cover forestry favourability between tree species are largely dependent on both species-specific differences in natural regeneration and natural regeneration differences between ecological models. Under realistic economic parameters, our model specification yields the result that continuous cover forestry is optimal for Norway spruce in both single- and mixed-species stands. In contrast, Scots pine favours rotation forestry in both single- and mixed-species stands. Economic preferability of species mixture cannot be deducted from physical overyielding. In addition, we demonstrate that economically optimal continuous cover forestry avoids “high grading”, i.e. selective harvesting that leads to a completely different and economically inferior outcome. Including the negative externalities of forestry on reindeer husbandry into the economic model favours continuous cover forestry in arctic Scots pine stands. A carbon price between €14–€20 tCO_2^{-1} is enough to imply that saving old-growth forests as carbon storages and reindeer pastures becomes optimal.

Keywords: continuous cover forestry, optimal rotation, mixed-species forests, carbon sequestration, boreal forestry, arctic forestry

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LIST OF ORIGINAL ARTICLES

This thesis consists of an introductory review followed by three original research articles. The articles published in scientific journals are reproduced with the permission of the publishers.

I	Parkatti V-P, Assmuth A, Rämö J, Tahvonen O (2019) Economics of boreal conifer species in continuous cover and rotation forestry. For. Policy. Econ. 100: 55–67. https://doi.org/10.1016/j.forpol.2018.11.003.
II	Parkatti V-P, Tahvonen O (2020) Optimizing continuous cover and rotation forestry in mixed-species boreal forests. Can. J. For. Res: 50. 1138–1151. https://doi.org/10.1139/cjfr-2020-0056.
III	Parkatti V-P, Tahvonen O (2021) Economics of multifunctional forestry in the Sámi people homeland region. J. Environ. Econ. Manag. 110: 102542. https://doi.org/10.1016/j.jeem.2021.102542.

AUTHOR’S CONTRIBUTION

Summary:
The author Vesa-Pekka Parkatti wrote the summary.

Articles I–III:
The author Vesa-Pekka Parkatti and Olli Tahvonen jointly planned articles **I–III**. The author conducted all computations and was mainly responsible for the analyses of the results for articles **I–III**. The author and Olli Tahvonen wrote articles **I–III** in cooperation. Aino Assmuth was involved in writing article **I.** Janne Rämö was involved in producing the optimization algorithms for article **I**.

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1 INTRODUCTION

1.1 Background and motivation

Forest resource usage currently faces major global challenges stemming from climate change (IPCC 2019) and biodiversity loss (Rands et al. 2010). Simultaneously, forest owner preferences are growing increasingly versatile (Häyrinen et al. 2015; Matilainen et al. 2019; Juutinen et al. 2020). Currently, most forest management in Fennoscandia is based on managing homogeneous even-aged forests with regeneration fellings such as clearcuts (Kuuluvainen et al. 2012). However, forest owner preferences towards e.g. forest amenity values may have a significant effect on forest owners' decision-making processes (Koskela and Ollikainen 2001). Responding to future challenges requires increased flexibility from forest management.

Current forestry methods in Fennoscandia can be divided into rotation forestry and continuous cover forestry. A rotation is the time between two regeneration fellings, e.g. between two clearcuts. In rotation forestry, a stand may be thinned multiple times within a rotation but is eventually felled for regeneration at the end of the rotation. Thus, revenues in rotation forestry are a combination of revenues from both thinnings and regeneration fellings. A forest is usually artificially regenerated after a regeneration felling. The artificial regeneration operations vary, mostly depending on forest type and tree species, but usually consist of at least ground preparation, tree seeding or planting, and tending of the seedling stand. The basic idea of continuous cover forestry is that a forest is never felled for regeneration. Thus, unlike rotation forestry, continuous cover forestry relies solely on the natural regeneration of trees and on revenues from thinning.

Discussion on continuous cover and rotation forestry was ongoing in the Fennoscandian region in the post-WW2 era (see Siiskonen 2007 and Lundmark et al. 2013). In Finland, this discussion resulted in centralized forest policy based on maximum sustainable yield and rotation forestry with mainly thinnings from below (i.e. harvesting of small-sized trees) (Kuuluvainen et al. 2012). However, from the present perspective, these policy changes were not based on interdisciplinary academic discussion, which appeared only much later (see e.g. Jalonen et al. 2006). At the beginning of 2014, after a "ban" on continuous cover forestry spanning many decades and taking the form of strict restrictions to forest management, the academic discussion led to the most recent renewal of Finnish forest legislation. This new forest legislation increased forest owners' freedom regarding forest management decisions and made continuous cover forestry practically feasible again (Forest act 1085/2013 and Forest decree 1308/2013). Recently, continuous cover forestry has gained much attention due to its argued high level of multifunctional properties compared to homogeneous rotation forestry, i.e. the simultaneous provision of timber and non-timber ecosystem services and biodiversity (EASAC 2017; Assmuth et al. 2018; Filyushkina et al. 2018; Peura et al. 2018; Tahvonen et al. 2019). Still, compared to rotation forestry, scientific literature on both the ecology and economics of continuous cover forestry remains scarce.

Historically, the largest obstacles for economic research on continuous cover forestry have been a lack of theoretically sound economic models, a lack of suitable ecological models, and lack of computer technology and optimization algorithms for complex optimization. In the past, forest economics have largely relied on separate models for continuous cover and rotation forestry, which has led to difficulties in comparing the two management regimes (see Hanewinkel 2002 and Tahvonen 2009). Currently, both analytical (Tahvonen 2015a,b) and numerical (Tahvonen and Rämö 2016) economic optimization models exist that simultaneously cover both continuous cover and rotation forestry and enable optimization between the two management regimes. Also, until recently, ecological models were unable to describe forest dynamics for both even- and uneven-aged stands. Luckily, a few such ecological models currently exist (i.e. models by Bollandsås et al. 2008 and Pukkala et al. 2011, 2013). Finally, due to advances in computer science and optimization algorithms, the optimization of continuous cover forestry has become technically feasible albeit still time-consuming. Given the future challenges concerning the use of forest resources, the recent scientific advances, and the new legal status of continuous cover forestry, there is an evident demand for scientific knowledge on continuous cover forestry.

1.2 Stand-level economics of continuous cover and rotation forestry

A stand, i.e. a uniform forest compartment, is the basic unit in stand-level forest economics and is usually one hectare in size and with exogenous economic parameters such as interest rate and prices. Traditionally, stand-level forest economic models are divided into groups based on the properties of the ecological models that they apply (see e.g. Valsta 1993). Firstly, whether the model unit size is a whole stand, a size class, or an individual tree. Secondly, whether the models are distance-dependent, i.e. include information on tree coordinates, or not. Thirdly, whether the models are deterministic or include stochasticity. Fourthly, whether the models are statistical-empirical or process-based. The history of stand-level forest economic models is characterized by a shift from applying simplistic univariate and whole-stand models for single tree species with one or a few optimized variables to detailed individual-tree models for mixed-species stands and an increasing number of optimized variables. However, independent of the ecological model type used, stand-level forest economic models may also be divided into three groups based on the generality of the model in the continuous cover and rotation forestry context. Firstly, economic models specifically for rotation forestry, secondly, economic models specifically for continuous cover forestry, and thirdly, economic models that simultaneously cover both rotation forestry and continuous cover forestry.

While many economists later ignored thinnings, the seminal Faustmann (1849) model for forestland value in rotation forestry includes income from both thinning and clearcuts. While Faustmann (1849) did not present an analytical solution to his model, the approach of calculating forestland value by discounting the net revenues over an infinite time horizon has since been shown to be theoretically correct for example by Ohlin (1921) and later Samuelson (1976). Interestingly, Viitala (2016) shows that the discovery of the now classic “Faustmann formula” was in fact discovered already several decades before Faustmann (1849) by Hossfeld (1805a,b). Clark (1976: 263–269) presented an analytical solution for a Faustmann (1849) model with thinning by defining thinning as a continuous-time optimal control problem. However, while analytically solvable, the Clark (1976) model omitted fixed thinning costs and applied a simplified whole-stand model for forest growth. The earliest economic studies on rotation forestry to include dynamic optimization of both timing and thinning intensity possibly date back to Amidon and Akin (1968) and Kilkki and Väisänen (1969); however, both still used whole-stand models. For a review of the early development of models with optimized thinning, see Valsta (1993). Early mixed-species rotation forestry studies in Finland (e.g. Valsta 1986) also applied whole-stand models. Valsta (1992a) used individual-tree models to optimize Norway spruce (*Picea abies* (L.) Karst.) rotation forestry and Valsta (1992b) included stochasticity into optimization with individual-tree models. Miina (1996) applied an individual-tree ecological model with distance dependency and stochasticity to optimize Scots pine (*Pinus sylvestris* L.) rotation forestry in drained peatlands. Hyytiäinen et al. (2005) used a distance-independent individual-tree model to optimize both juvenile density and thinnings in Scots pine stands under rotation forestry. Hyytiäinen et al. (2004) applied a detailed process-based distance-independent individual-tree model to optimize Scots pine stand management in rotation forestry. Using distance-independent process-based individual-tree ecological growth models, Niinimäki et al. (2012) and Tahvonen et al. (2013) optimized the thinning timing, thinning intensities, initial densities, and rotation lengths for pure Norway spruce and Scots pine stands in rotation forestry, respectively. Pihlainen et al. (2014) added carbon storage to the model by Tahvonen et al. (2013) and optimized rotation forestry management of Scots pine stands including revenues from both timber production and carbon sequestration. Recently, Pyy et al. (2020) presented a size-structured transition matrix model based on diameter breast height that also includes height variations within diameter classes. However, the economic model by Pyy et al. (2020) omits all forestry beyond the ongoing rotation (cf. Faustmann 1849).

One early treatise on continuous cover forestry is from a French forester de Liocourt (1898), who introduced the idea of a now classic reverse J-shaped diameter distribution for continuous cover forestry size-class structure. Compared to rotation forestry, the optimization of continuous cover forestry is generally a more complex problem. This complexity has resulted in many simplifications and in the tradition of using size-structured ecological models based on diameter breast height instead of more computationally demanding individual-tree models. The static investment-efficient model presented by Adams (1976) is one simplification for tackling the complexity of continuous cover forestry, and it has since seen widespread use in many forms by e.g. Buongiorno and Michie (1980), Chang (1981), Bare and Opalach (1987), Buongiorno et al. (1995), and Pukkala et al. (2010). However, the flawed theoretical basis of the static investment-efficient model was pointed out by Haight (1985) already in the 1980s. Another common simplification is the use of an a priori steady-state endpoint in the optimization. In their seminal paper, Adams and Ek (1974) apply the marginal value model by Duerr and Bond (1952) to determine the optimal steady-state growing stock of a size-structured pure single-species stand and then optimize the transition to this fixed steady-state endpoint in three periods. However, the suboptimality of the fixed endpoint optimization was pointed out already by e.g. Haight and Getz (1987). While most early studies applied the investment-efficient model and fixed endpoint optimization, some studies were able to dynamically optimize continuous cover forestry in a general form without such simplifications, yet still applying fixed harvesting intervals. For single-species stands, such studies include e.g. Haight (1985) and Haight et al. (1985), both of which apply size-structured ecological models. For mixed-species stands, such studies include Haight and Getz (1987), who apply size-structured ecological models, and Haight and Monserud (1990a,b), who use individual-tree ecological models. In Fennoscandia, applying fixed harvesting intervals and size-structured ecological models, Tahvonen (2009), Tahvonen et al. (2010), and Rämö and Tahvonen (2014) dynamically optimized continuous cover forestry in pure single-species stands, while Rämö and Tahvonen (2015) also optimized mixed-species stands. Wikström (2000) and Rämö and Tahvonen (2017) both studied pure single-species continuous cover forestry using size-structured ecological models but also optimized the harvest timing.

Comparisons between continuous cover and rotation forestry have provided challenges to which Hanewinkel (2002) and Tahvonen (2009) offer discussion. One branch of research aiming to cover both management regimes has focused on comparing predetermined transformation simulations of even-aged rotation forestry stands into uneven-aged continuous cover forestry stands. As simulations are computationally less demanding compared to optimization, the studies commonly use detailed individual-tree models. For example, Knoke and Plusczyk (2001) use distance-dependent individual-tree ecological growth models to simulate transformations of even-aged Norway spruce stands to uneven-aged Norway spruce stands. Similarly, using distance-dependent individual-tree ecological growth models, Hanewinkel (2001) studies the transformation of even-aged Norway spruce stands to uneven-aged Norway spruce and beech mixtures. Juutinen et al. (2018) use a process-based individual tree ecological model to compare the profitability of Norway spruce management in continuous cover and rotation forestry using various harvesting intervals and intensities. Kellomäki et al. (2019) use a detailed process-based ecological model to study pure Norway spruce stand management by comparing both timber revenues and carbon storage properties of continuous cover and rotation forestry simulations. While simulations can be used to study existing forest management practices, they are dependent on the predetermined forest management schedules applied. Thus, comparisons between simulations without optimization may only provide limited answers to the optimality of management regimes.

Chang (1981) presented an early attempt to optimize between continuous cover and rotation forestry by using a simplistic whole-stand growth model and the later theoretically flawed static investment-efficient model (see e.g. Haight 1985). Similarly, Pukkala (2010) applied the static investment-efficient model together with an individual-tree ecological model to “optimize” the choice between continuous cover and rotation forestry. Another branch of research has approached the optimization between continuous cover and rotation forestry by first solving the economically optimal continuous cover forestry solution and then comparing this solution to a solution where the stand is converted into rotation forestry. If the conversion is never optimal, continuous cover forestry is considered optimal. However, typically in these studies, the rotation forestry solution is solved by applying a Faustmann (1849) -type model with thinning, where the management regime is predetermined. These studies include e.g. Haight and Monserud (1990a,b) and Hyytiäinen and Haight (2010), who both study mixed-species stands using individual-tree ecological models and fixed harvesting intervals. Using similar model structure, Wikström (2000) studied single-species Norway spruce stands using individual-tree models but also optimizing harvest timing.

Tahvonen (2009) presented a theoretical size-structured economic model capable of producing both continuous cover and rotation forestry endogenously, yet still using fixed harvesting intervals. Tahvonen (2015a,b) developed a unified continuous-time analytically solvable model that allows fully flexible optimization between continuous cover and rotation forestry. Tahvonen and Rämö (2016) presented a discrete-time numerically solvable single-species size-structured version of the analytical Tahvonen (2015a,b) model including fully flexible optimization of harvesting timing and management regime. Assmuth et al. (2018) expanded the model by Tahvonen and Rämö (2016) to include carbon storage and allowing simultaneous optimization of both timber production and carbon storage. Recently, Tahvonen et al. (2019) expanded the model by Tahvonen and Rämö (2016) to include mixed-species stands and a valuation of ecosystem services.

In sum, a large proportion of continuous cover forestry research has relied on theoretically flawed proven models and methods. The existing optimization literature covering continuous cover forestry that is considered theoretically sound has heavily focused on studying pure single-species stands, applying fixed harvesting intervals, and concentrating on timber production.

1.3 Aims and objectives

The overall aim of this dissertation is to further develop the economics of rotation forestry and continuous cover forestry that has largely focused on studying single-species Norway spruce stands. The dissertation expands the existing literature in multiple ways by studying the effects of different tree species (in both single- and mixed-species stands), ecological growth models, growth conditions, and non-timber ecosystem services on the economically optimal choice between continuous cover and rotation forestry.

This dissertation consists of three original research articles. The main objectives of each article are listed as follows:

Article I

- to study the differences in economically optimal stand-level forest management between pure Norway spruce and Scots pine stands
- to study the differences in the continuous cover forestry favourability between pure Norway spruce and Scots pine stands
- to study the effects of ecological growth models on economically optimal solutions

Article II

- to study economically optimal stand-level forest management in mixed-species stands
- to study how physical and economic outputs differ between species mixtures
- to study the economic rationality of “high grading” selective harvesting
- to study the economic rationality of thinning

Article III

- to study the economically optimal management regime when simultaneously considering revenues from timber production and carbon sequestration and negative externalities from forestry on reindeer husbandry
- to study the economic rationality of conventional forest management in upper Lapland
- to study cutoff carbon prices that render carbon storage and reindeer husbandry preferable compared to timber production in upper Lapland
- to study the economic rationality of the “carbon debt” and “payback period” concepts
- to study the possible socially preferable forest management in upper Lapland

2 MODELS AND METHODS

This dissertation mainly uses interdisciplinary economic-ecological optimization, in which species-specific ecological models for forest dynamics are coupled with economic optimization models. This method of “model coupling” has been reviewed as an effective way of conducting interdisciplinary research in resource economics (MacLeod and Nagatsu 2016, 2018).

2.1 Economic optimization models

This dissertation (articles **I**–**III**) describes the forest state and dynamics with a size-structured version of a discrete-time ecological transition-matrix model that has background already in Leslie (1945) and Usher (1966, 1969). Let $x_{jst},\ j = 1,...,l,\ s = 1,...,n,\ t = t_0, t_0 + 1,...T$ denote the number of trees of species *j* in size class *s* at the beginning of period *t*. Now, the stand state at period *t* can be described with the following matrix:

$$\mathbf{x}_t = \begin{bmatrix} x_{11t} & x_{12t} & \cdots & x_{1nt} \\ x_{21t} & x_{22t} & \cdots & x_{2nt} \\ \vdots & \vdots & \ddots & \vdots \\ x_{l1t} & x_{l2t} & x_{l3t} & x_{lnt} \end{bmatrix}.$$

During period *t*, the development of a forest stand without management is described by species and size-class-specific diameter growth given by $I_{js}(\mathbf{x}_t),\ j = 1,...,l, s = 1,...,n-1, t = t_0.,,,T$, species and size-class-specific mortality given by $\mu_{js}(\mathbf{x}_t),\ j = 1,...,l, s = 1,...,n, t = t_0.,,,T$ and species-specific ingrowth (i.e. natural regeneration) given by $\phi_j(\mathbf{x}_t),\ j = 1,...,l, t = t_0.,,,T$. Including ingrowth $\phi_j\left(\mathbf{x}_t\right)$ is necessary for continuous cover forestry to be a feasible management option. The proportion of species *j* trees that moves from size class *s* to $s+1$ during period *t* is obtained by dividing the periodic diameter increment with the width of the size class τ, i.e. $\alpha_{jst} = \tau^{-1}(I_{js}(\mathbf{x}_t)),\ j = 1,...,l, s = 1,...n-1, t = t_0,...,T$. Thus, a size-class structured transition matrix model assumes that trees are evenly distributed within size classes. The use of transition matrix models in the study of forests is widely established all over the world (Liang and Picard 2013). Still, like all models, transition matrix models also have their limitations of which Liang and Picard (2013) and Picard and Liang (2014) offer a discussion.

The number of harvested and felled trees of species *j*, from size class *s*, at the end of time period *t* are denoted by h_{jst} and k_{jst}, respectively. The number of harvested trees describes the number of trees that are cut to length and hauled to the intermediate storage site. In contrast, the number of felled trees describes the number of trees that are felled without further utilization. The option to fell a tree is included, as felling a tree is a cheaper option than harvesting it for non-commercial tree species.

Harvesting revenues (€/ha) from thinnings and regeneration fellings (e.g. clearcut) are denoted by $R(\mathbf{h}_t)$ and $R(\mathbf{h}_T)$ and are specified as

$$R(\mathbf{h}_t) = \sum\nolimits_{j=1}^{l} \sum\nolimits_{s=1}^{n} h_{jst}\left(v_{1sj} p_{1j} + v_{2sj} p_{2j}\right),\ t = t_0, t_0+1, \ldots, T \quad (1)$$

where p_{1j} and p_{2j} describe the roadside prices (€/m^3) of species *j* pulpwood and sawlogs, respectively. Similarly, v_{1sj} and v_{2sj} describe pulpwood and sawlog volumes (m^3) in size-class *s* for species *j*, respectively. Separate variable harvesting costs for thinnings and regeneration fellings (clearcut) are calculated using an empirical model by Nurminen et al. (2006) and are denoted by $C_{th}(\mathbf{h}_t, \mathbf{k}_t)$ and $C_{cc}(\mathbf{h}_T, \mathbf{k}_T)$, respectively. According to our specification, harvesting costs are set higher for thinning than for regeneration felling. The fixed costs of harvesting (€/ha) are denoted by C_f and consist of the transportation of logging equipment and planning. The discrete-time discount factor is given by $b^{\Delta} = 1/(1+r)^{\Delta}$, where Δ is the period length (5 years) and *r* is the interest rate. To optimize harvest timing, we include a binary variable $\delta_t : Z \in \{0,1\}, t = t_0, t_0+1, \ldots$ and Boolean operators $h_{jst} = \delta_t h_{jst}, k_{jst} = \delta_t k_{jst}$. Now, when $\delta_t = 1$, fixed harvesting costs occur and the level of harvests and fellings may obtain positive values. When $\delta_t = 0$, no fixed costs occur, but harvests and fellings are also zero. Let *w* describe the present value of artificial regeneration costs occurring before t_0. Now, by denoting the value of bare land by *J* we can present the optimization problem as follows:

$$\max_{\{h_{jst}, k_{jst}, \delta_t, T \in [T,\infty)\}} J = \frac{-w + \sum_{t=t_0}^{T-1} [R(\mathbf{h}_t) - C_{th}(\mathbf{h}_t, \mathbf{k}_t) - \delta_t C_f] b^{\Delta(t+1)} + [R(\mathbf{h}_T) - C_{cc}(\mathbf{h}_T, \mathbf{k}_T) - \delta_T C_f] b^{\Delta(T+1)}}{1 - b^{\Delta(T+1)}} \quad (2)$$

subject to

$$x_{j,1,t+1} = \phi_j\left(\mathbf{x}_t\right) + \left[1 - \alpha_{j1}\left(\mathbf{x}_t\right) - \mu_{j1}\left(\mathbf{x}_t\right)\right] x_{j1t} - h_{j1t} - k_{j1t},\quad j = 1, \ldots, l,\ t = t_0, \ldots, T, \quad (3)$$

$$x_{j,s+1,t+1} = \alpha_{js}\left(\mathbf{x}_t\right) x_{jst} + \left[1 - \alpha_{j,s+1}\left(\mathbf{x}_t\right) - \mu_{j,s+1}\left(\mathbf{x}_t\right)\right] x_{j,s+1,t} - h_{j,s+1,t} - k_{j,s+1,t},\ j = 1, \ldots, l,\ s = 1, \ldots, n-1,\ t = t_0, \ldots, T, \quad (4)$$

the Boolean operators

$$h_{jst} = h_{jst}\delta_t, k_{jst} = k_{jst}\delta_t,\ j = 1, \ldots, l, s = 1, \ldots, n, t = t_0, \ldots, T, \delta_t : Z \in \{0,1\} \quad (5)$$

and initial stand state

x_{jst_0} are given. (6)

Also, nonnegativity constraints $x_{jst} \geq 0, h_{jst} \geq 0,\ \ k_{jst} \geq 0, j = 1,...l,\ \ s = 1,...,n, t = t_0,...,T$ must hold. Now, the optimal rotation period T determines the optimal choice between continuous cover and rotation forestry. When optimal T is infinitely long, the optimal solution is continuous cover forestry and when optimal T is finite, the optimal solution is rotation forestry.

In article **II**, we consider mixed-species stands of up to four tree species where $j = 1, 2, 3, 4.$ In contrast, in articles **I** and **III,** we study single-species stands where j=1 and the possibility to fell a tree is not included. In articles **I** and **II,** we apply 11 size classes based on diameter breast height, ranging from 2.5 cm (midpoint) to 52.5 cm in 5-cm intervals. In article **III**, we use 7 size classes that range from 7.5 cm to 37.5 cm in 5-cm intervals. In articles **I** and **II**, the fixed cost of harvesting is €500 ha^{-1} whereas the fixed cost is set to €250 ha^{-1} in article **III**. The fixed costs in article **III** are set lower than in articles **I** and **II** to factor in the larger average forest compartment sizes in northern Finland compared to central Finland. In articles **I** and **III**, at t_0, the stand consists of 1750 trees per hectare in the 7.5-cm diameter class. In article **I**, the timing of t_0 varies between 15 and 30 years, depending on forest type/fertility, whereas $t_0 = 45$ years in article **III**. In article **II**, $t_0 = 20$ years and at t_0 the stand consists of 1750 ha^{-1} artificially regenerated trees and 250 ha^{-1} naturally regenerated trees per species in the 7.5-cm diameter class.

In articles **I** and **II,** the stand is artificially regenerated after a clearcut at T. In contrast, in article **III,** the stand is regenerated with a seedling felling in which we require seed trees to be left on the stand during the regeneration felling at T to produce new saplings. Thus, in article **III,** the initial stand state at $t = 0$ also consists of seed trees that are then harvested 25 years later. A seedling felling decreases both the ground lichens and arboreal lichens that grow in trees so that it takes decades for the lichen biomass to restore itself. As lichens are an important winter energy source for reindeer, seedling fellings cause negative externalities on reindeer husbandry. In article **III**, w is replaced with W, which describes the net present value of harvesting the seed trees left during the previous seedling felling, artificial regeneration costs, and the negative externality costs of seedling felling on reindeer husbandry.

In article **III**, following Assmuth et al. (2018), in addition to timber revenues we also include revenues from carbon sequestration. Let $p_c \geq €0$ tCO$_2^{-1}$ denote the social, economic value of carbon. The merchantable timber of the stand at time t is denoted by ω_t. Let ρ transform the timber volume of a tree into tree dry mass and expansion factor η convert the dry mass into whole-tree dry mass (that also includes non-merchantable materials, i.e. foliage, branches bark, stumps, and roots). Thus, whole-stand biomass at the beginning of t equals $\rho\eta\omega_t$ in tonnes of dry mass. The CO$_2$ content of a unit of dry mass is denoted by θ. Let $y_{1,t}$ and $y_{2,t}$ denote the dry mass of harvested sawtimber and pulpwood, respectively. Similarly, the dry mass of dead tree matter from natural mortality and harvesting residues are given by $y_{3,t}$ and $y_{4,t}$, respectively. Now, let $g_d, d = 1, 2, 3 = 4$ denote the decay rates of sawlogs, pulpwood, and dead tree matter, respectively. The present value of future emissions from sawtimber, pulpwood, and dead tree matter is given by $\beta_d(r) = g_d / (g_d + r)$ (Assmuth et al. 2018). Now, the value of net carbon sequestration during a period t can be given as $Q_t = p_c\theta\left[\rho\eta(\omega_{t+1} - \omega_t) + \sum_{d=1}^{4}(1-\beta_{dr})y_{dt}\right]$. Thus, in article **III**, to include the economics of carbon sequestration, we add a term $\sum_{t=0}^{T} Q(\mathbf{x}_t, \mathbf{h}_t) b^{\Delta(t+1)} \left(1-b^{\Delta(T+1)}\right)^{-1}$ into the objective functional (2).

2.2 Ecological models

This dissertation applies two size-structured statistic-empirical distance-independent and deterministic ecological models, i.e. the models by Pukkala et al. 2013 and Bollandsås et al. 2008. In addition, in article **II**, we apply an ingrowth model for birch by Pukkala et al. (2011). The Pukkala et al. (2011) model for birch ingrowth was chosen after consulting with the lead author of both the Pukkala et al. (2011) and Pukkala et al. (2013) models. All models used include parameter values that allow the models to be calibrated for various growth conditions. The exact forms of the ecological models used are presented separately in articles **I**–**III**. The ecological models include separate, density-dependent, and species-specific models for diameter increment $I_{js}(\mathbf{x}_t)$, natural mortality $\mu_{js}(\mathbf{x}_t)$, and ingrowth $\phi_j(\mathbf{x}_t)$. The periodic time step in all of the ecological models is five years.

While the mathematical formulations for diameter increment and natural mortality differ between the ecological models used, the greatest difference between the models stems from the description of ingrowth. This difference is negligible between the models by Pukkala et al. (2013) and Pukkala et al. (2011). Pukkala et al. (2013) describes ingrowth as the number of trees that reach breast height (trees that enter our size class 1), while the Pukkala et al. (2011) model describes ingrowth as the number of trees reaching a diameter breast height of 0.5 cm (trees that enter our size class 1). In contrast, the Bollandsås et al. (2008) model describes ingrowth as the number of trees that reach a diameter breast height of 5.0 cm (trees that enter our size class 2). Thus, the model by Bollandsås et al. (2008) does not contain information about trees smaller than 5.0 cm in diameter.

2.3 Data and computational optimization methods

Table 1 presents the models and data used in articles **I**–**III**. Article **I** studies pure single-species Norway spruce and Scots pine stands in central Finland and applies the ecological models by Pukkala et al. (2013) and Bollandsås et al. (2008). Article **II** studies mixed-species stands with up to four tree species, i.e. Norway spruce, Scots pine, silver birch (*Betula pendula* Roth) and Eurasian aspen (*Populus tremula* L.). in central Finland and use the ecological models by Pukkala et al. (2011, 2013). Article **III** studies pure single-species Scots pine stands in upper Lapland, using the ecological model by Bollandsås et al. (2008). In articles **I** and **II**, revenues come solely from timber production, whereas in article **III** we also include revenues from carbon sequestration and the negative externalities of forestry on reindeer husbandry.

The harvest timing variables $\delta_t : Z \in \{0,1\}$ in the objective functional (2) are integers, while the variables for harvesting h_{jst} and felling $k_{jst}, j = 1,...,l, s = 1,...,n, t = t_0, t_0 + 1,...$ are continuous. This makes the optimization a tri-level nonlinear mixed-integer problem. Rotation length is the highest-level problem in the tri-level problem, harvest timing is the middle-level problem, and harvest intensity is the lowest-level problem. The optimal rotation is solved by varying T until a highest bare land value is found. Optimization is performed using AMPL programming language and Knitro optimization software (versions 10.1 and

10.3). Given a specific rotation length *T*, we apply bi-level optimization (Colson et al. 2007) for harvest timing and intensities. Harvest timing is solved using genetic- and hill-climbing algorithms, while the harvest intensities are solved by gradient-based methods (Byrd et al. 2006) of the Knitro software. Due to potential nonconvexities, we apply multiple random initial points for each of the lowest-level problems. Determination of optimal *T* defines the optimal management regime and when optimal *T* is infinitely long, the optimal solution is continuous cover forestry. In contrast, when optimal *T* is finite, the optimal solution is rotation forestry. In articles **I** and **II**, finite rotation solutions are searched for between $T \in [40,180)$ and between $T \in [80,250)$ in article **III**. The infinite rotation, i.e. continuous cover forestry solutions, is solved by lengthening T until additional lengthening no longer changes the solution towards a steady state. Given four tree species, the optimization of a mixed-species continuous cover forestry solution may take up to 170 hours when using an Intel ® Xeon ® E5-2643 v3 @3.40GHZ, 24 logical processor computer.

Table 1: Models and data used

Article	I	II	III
Ecological models			
Pukkala et al. (2011)		x	
Pukkala et al. (2013)	x	x	
Bollandsås et al. (2008)	x		x
Geographical location			
Central Finland	x	x	
Upper Lapland			x
Tree species			
Single-species	x	x	x
Mixed-species		x	
Norway spruce	x	x	
Scots pine	x	x	x
Silver birch		x	
Eurasian aspen		x	
Revenues			
Timber production	x	x	x
Carbon storage			x
Externalities			
On reindeer husbandry			x

3 RESULTS

3.1 Economics of boreal conifer species in continuous cover and rotation forestry (I)

Norway spruce and Scots pine are the two economically most significant tree species in Finland. However, there are significant ecological differences between the two species, most notably in their shade tolerances. While Norway spruce is considered a shade-tolerant species, Scots pine is not. Shade tolerance benefits the survivability of saplings (see e.g. Mason et al. 2004), which is crucial for the feasibility of continuous cover forestry that relies on natural regeneration. In article **I**, we study the differences in continuous cover forestry favourability between pure Norway spruce and Scots pine stands. Furthermore, we apply both the Pukkala et al. (2013) and the Bollandsås et al. (2008) statistical-empirical ecological models to study the effect of ecological models on economically optimal solutions.

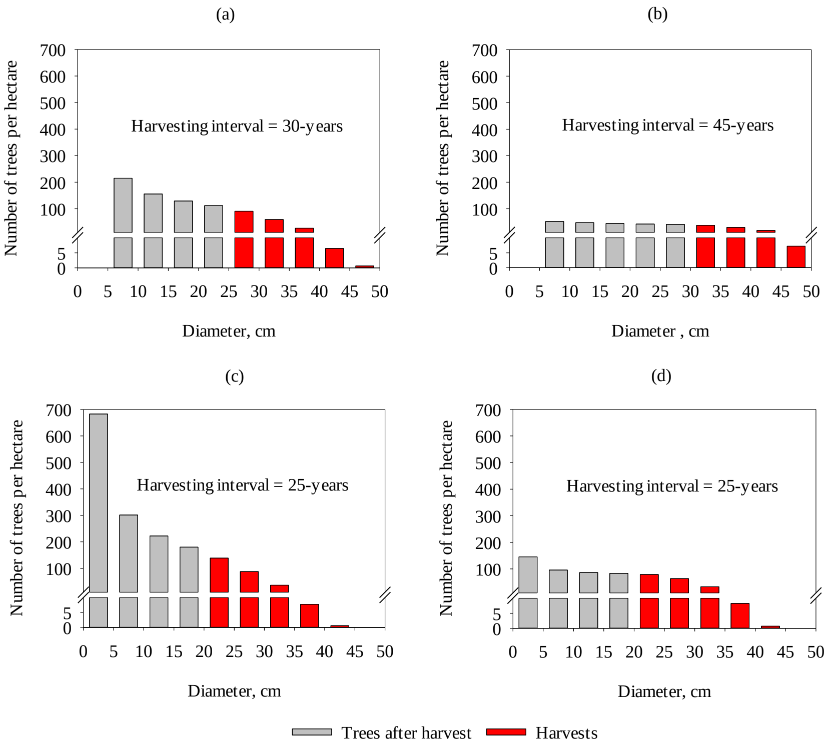

Figure 1: Economically optimal steady-state stand structures with a 1% interest rate for (a) Norway spruce with the Bollandsås et al. (2008) model, (b) Scots pine with the Bollandsås et al. (2008) model, (c) Norway spruce with the Pukkala et al. (2013) model, and (d) Scots pine with the Pukkala et al. (2013) model.

Note: 1% interest rate.

According to our results, Norway spruce is more favourable towards continuous cover forestry compared to Scots pine, independent of the ecological model used. However, the extent of this favourability and the characteristics of the economically optimal solutions are strongly dependent on the ecological model used. Figure 1 presents the optimal continuous cover steady-state stand structures in both pure Norway spruce and Scots pine stands, with both the Pukkala et al. (2013) and Bollandsås et al. (2008) models. Due to higher ingrowth at the steady state, Norway spruce has a larger number of trees in the small size classes than Scots pine. For similar reasons, the Pukkala et al. (2013) model has a larger number of small trees in the small size classes than the Bollandsås et al. (2008) model. Independent of the tree species considered, the model by Pukkala et al. (2013) is found to be more favourable toward continuous cover forestry than the model by Bollandsås et al. (2008). However, with artificial regeneration costs of over €1000 ha^{-1} and an interest rate of 3%, continuous cover forestry becomes economically optimal for both tree species independent of the ecological model used. Furthermore, all the economically optimal thinnings are thinnings from above (i.e. harvesting of large-sized trees), independent of the ecological model, tree species, or management regime considered.

In the economically optimal continuous cover forestry steady states of pure Scots pine stands, the post-harvest basal areas are extremely low with both ecological models applied. This is mostly caused by the low ingrowth of Scots pine. Thus, to gain sufficiently high ingrowth for continuous cover forestry, the post-harvest basal area in a pure Scots pine stand must be kept low through heavy thinning. Thus, the low stand basal areas in the economically optimal continuous cover forestry steady states may violate the current legal lower bound restrictions on basal area.

The main findings of article **I** include:

- Continuous cover forestry is economically optimal in many cases
- Ecological models have a strong effect on economically optimal solutions mostly due to differences in ingrowth
- Tree species strongly affect economically optimal solutions mostly due to differences in ingrowth
- Continuous cover forestry is less favourable for Scots pine compared to Norway spruce

3.2 Optimizing continuous cover and rotation forestry in mixed-species boreal forests (II)

Most of the economic studies on both rotation forestry and continuous cover forestry concentrate on pure single-species stands. However, for example, there are approximately 30 different naturally regenerating tree species in Finland (Hämet-Ahti et al. 1992). Thus, maintaining a pure single-species stand may require active forestry operations that studies on pure single-species stands are unable to capture. In addition, mixed-species stands form a substantial proportion of boreal forests. For example, half of the forests in Finland and Sweden can be classified as mixed-species forests (Natural Resources Institute Finland 2018; Nilsson et al. 2019).

In article **II**, we study the management of boreal mixed-species stands with up to four tree species. The tree species included are Norway spruce, Scots pine, silver birch, and Eurasian aspen. We study a fertile forest stand that is initially artificially regenerated for Norway spruce but which may also experience natural regeneration by other native tree species.

Given realistic artificial regeneration costs, continuous cover forestry is found to be economically optimal, independent of the species mixture studied. At the economically optimal steady state, Norway spruce remains a dominant species albeit broadleaf species may account up to 40% of the stand volume (Figure 2a). Scots pine favours rotation forestry and its economic significance at the continuous cover forestry steady state is negligible. Harvesting all Norway spruce and silver birch trees once they have reached 20 cm in diameter is always optimal at the continuous cover forestry steady state. Increasing the number of tree species other than low-value or non-commercial Eurasian aspen generally increases the profitability of forestry. While mixed-species stands may produce overyielding (see e.g. Pukkala et al. 1994 and Lu et al. 2016), we show that the physical overyielding output (m^3) does not reveal the economic profitability of a species mixture.

Increasing the number of tree species in a stand generally increases the economically optimal post-harvest basal areas (Figure 2b). Thus, in mixed-species stands, fulfilling lower bound requirements for basal area in the current forest legislations can be achieved without costs. In addition, we demonstrate the high economic importance of thinning in boreal forestry. By omitting thinning and optimizing only for rotation length, the bare land value may decrease up to 73%. The economic significance of thinning increases with the presence of Eurasian aspen and under higher interest rates.

Managing single-species stands by actively felling the naturally regenerating other native tree species causes noticeable economic loss. Thus, while Eurasian aspen is found to decrease the bare land value, it is felled without further utilization only when it is given no commercial value. Figure 3 demonstrates an optimal solution when the felling of non-commercial Eurasian aspens is ruled out, i.e. harvesting is carried out as “take the best, leave the rest” -type of high grading. As a result, the stand becomes dominated by large/old Eurasian aspen trees (Figure 3a, c), both revenues and yield diminish (Figure 3b), and bare land value decreases. These results demonstrate that economically optimal continuous cover forestry avoids “high grading”.

The main findings of article **II** include:

- Based on our model setup, economically optimal solutions under realistic economic parameters produce continuous cover forestry
- Scots pine favours rotation forestry in mixed-species stands
- Omitting thinning causes noticeable economic loss
- Physical overyielding does not reveal economic profitability of a species mixture
- Economically optimal continuous cover forestry avoids “high grading”

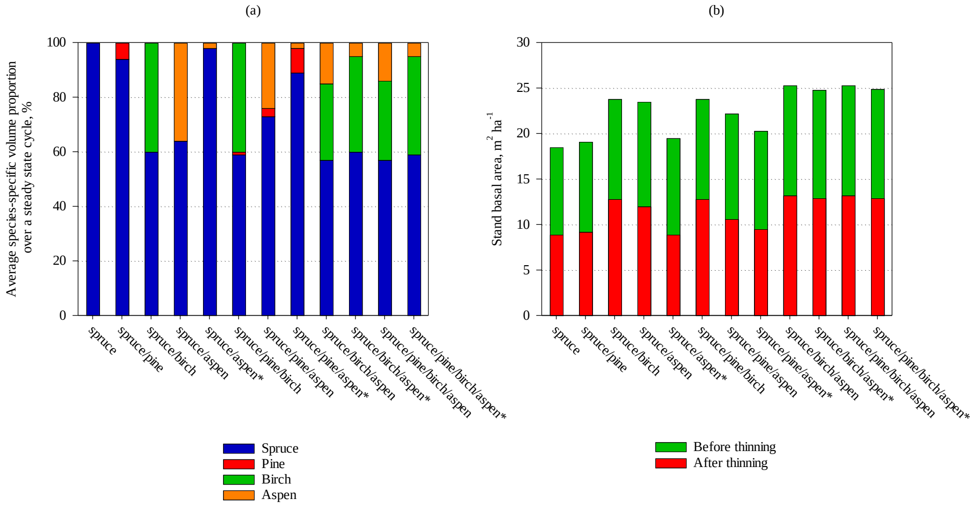

Figure 2: Average species-specific volume proportions over a steady-state cycle (a) and steady-state stand basal areas before and after thinning (b).

Note: 3% interest rate. aspen* = aspen without commercial value.

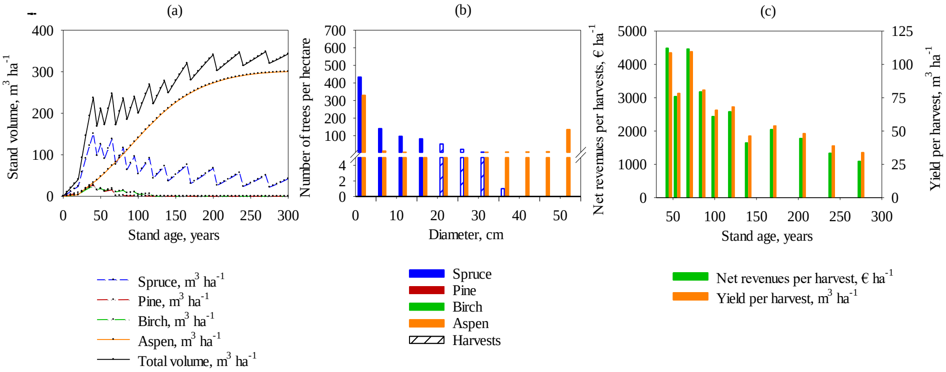

Figure 3: Results of not felling non-commercial Eurasian aspen trees. (a) stand volume development, (b) stand structure at the age of 205 years, and (c) development of net revenues and yield per harvest.

Note: 3% interest rate.

3.3 Economics of multifunctional forestry in the Sámi people homeland region (III)

Article **III** studies the economics of Scots pine forests in the Sámi peoples' homeland region of the arctic Finnish upper Lapland. The upper Lapland region is an example of an area with multiple, often competing land uses. For example, forests in the area are used for commercial timber production while forests also store carbon and the lichen growing in old-growth forests is the main winter energy source for semi-domesticated reindeer (Pekkarinen et al. 2015). Thus, conflicts occasionally emerge between the different land-use parties, especially between reindeer herders and government-operated forestry. The climate in Lapland is harsh, causing forest growth to be low, indicating low profitability of commercial timber production. However, no studies on the profitability of commercial timber production in the area currently exist. In article **III**, we use an economic model that simultaneously includes timber production, carbon storage, negative externalities of forestry on reindeer husbandry, and the optimization between continuous cover and rotation forestry.

Without negative externalities on reindeer husbandry, and with a 1% interest rate and €0–€40 tCO_2^{-1} carbon price, the economically optimal solution is rotation forestry with a long optimal rotation. Including an estimate of the negative externalities on reindeer husbandry further lengthens the optimal rotations. In contrast, under a 3% interest rate the optimal solutions are always continuous cover forestry, independent of carbon price or the negative externalities on reindeer husbandry. Furthermore, a high enough carbon price causes all harvesting to cease completely, i.e. forests are used solely for carbon storage and as reindeer pastures.

According to the silvicultural guidelines of Metsähallitus (2014), conventional forest management in the area is mainly based on rotation forestry with thinnings from below. Compared to economically optimal solutions, this conventional forest management has noticeably lower economic profitability. Under conventional forest management, the positive net present value of timber production is solely based on the utilization of existing forests and any operations aiming to continue timber production after harvesting of the initial seed trees yields a negative net present value. Thus, if the aim is to solely maximize timber revenues, an optimal solution would be a clearcut without investments in future timber production. However, this option is ruled out by Finnish forest legislation (Forest Decree 1308/2013) that requires stand regeneration. Thus, due to the questionable economic sustainability, we label this form of forest management as “forest capital mining”. Switching from conventional forest management to thinning from above, to longer rotations, and to continuous cover forestry increases the profitability of forestry. Furthermore, continuous cover forestry offers possibilities to integrate timber production, carbon storage, and reindeer pasture maintenance.

While clearcutting an old-growth forest may produce high immediate timber revenues, such conversions of old-growth forests to forestry can been criticized e.g. from a carbon storage perspective. A seminal paper by Fargione et al. (2008) has since produced a large literature concentrating on the concepts of “carbon debt” and “payback period” (see e.g. Malcolm et al. 2020). The “carbon debt” concept is used to describe the initial carbon releases from clearcutting an existing old-growth forest and converting it to other uses such as forestry or agriculture. The “payback period” concept is used to describe the time it takes to repay this initial carbon release with biofuel production and substitution of fossil fuels. While such concepts are useful in questioning the carbon neutrality of converting existing old-growth forests to forestry, they lack all general economic approaches and determining whether a “payback period” of old-growth conversion is long or not remains subjective. Furthermore, the concept of mitigating climate change by substituting fossil fuels with biofuels has been recently heavily criticized (see Leturcq 2020). We present a dynamic economic approach for land conversions. In our approach, timber usage is based on actual empirical data and the objective is a co-production of timber and carbon storage. With our approach, the profitability of old-growth conversion depends mainly on the carbon price and interest rate used. Figure 4a presents the carbon storage development when converting an old-growth forest to timber production with conventional forest management, while Figure 4b presents the corresponding “break-even” curves for positive net present value. Under a 3% interest rate, a €20 tCO_2^{-1} carbon price is enough to render conserving an old-growth forest as carbon storage optimal

(Figure 4b). Including an estimate of the negative externalities of forestry on reindeer husbandry further decreases the profitability of forestry and decreases the carbon choke price that renders timber production nonoptimal. Figure 4 shows that while reaching the initial carbon storage level takes an entire rotation, the conversion may be economically optimal. Furthermore, even if the carbon payback period would be infinitely long, the old-growth conversion can be economically optimal. Thus, our dynamic economic approach does not have any linkages to the "carbon debt" and "payback period" concepts.

The main findings of article **III** include:

- Economically optimal solutions are either rotation forestry with a long rotation length or continuous cover forestry
- Conventional forest management can be labelled "forest capital mining", as it is based on the utilization of existing trees and is not economically sustainable
- The carbon choke prices that render harvesting nonoptimal are smaller under conventional forest management compared to economically optimal solutions
- the economically grounded carbon choke prices have no connection to the concepts "payback period" and "carbon debt"

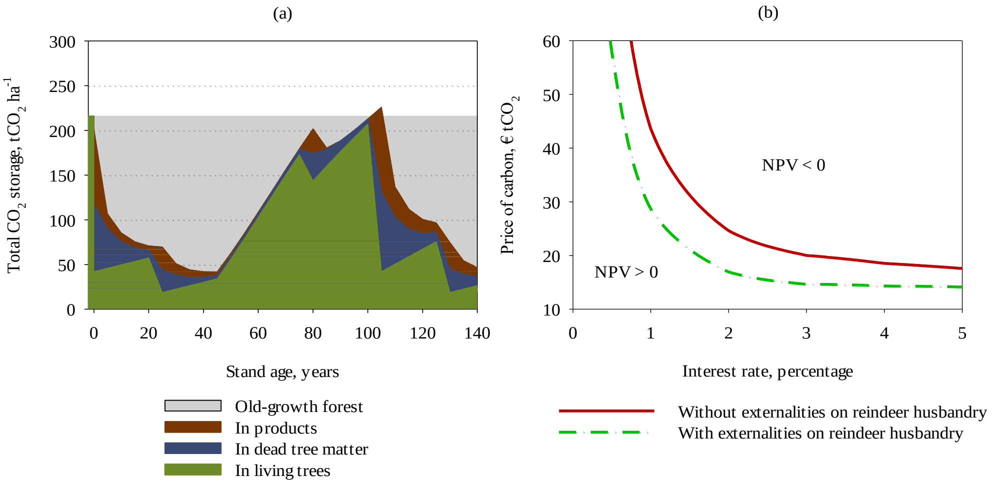

Figure 4: (a) Development of carbon storage in the stand and wood products when applying conventional forest management to existing old-growth forests and (b) the corresponding break-even curves for the positive net present value (NPV) under carbon pricing.

4 DISCUSSION

4.1 Economically optimal management regime

In this dissertation (articles **I**–**III**), the economically optimal management regime, i.e. the optimal choice between continuous cover and rotation forestry, is determined endogenously. The economically optimal management regime depends on tree species, growth conditions, and economic parameters, but also on the ecological growth models used. When maximizing timber revenues under realistic economic parameters, continuous cover forestry becomes economically optimal for Norway spruce in both single- and mixed-species stands (articles **I** and **II**). In contrast, Scots pine favours rotation forestry in both single- (articles **I** and **III**) and mixed-species stands (article **II**). Under a low interest rate (1%), the economically optimal solutions for a pure Scots pine stand are always rotation forestry, independent of the ecological growth model and growth conditions studied (articles **I**–**III**).

Current Finnish forest legislation allows for continuous cover forestry if forest type and location-specific lower bound restrictions on basal area are fulfilled (Forest decree 1308/2013). According to the results of this dissertation, economically optimal continuous cover forestry may lead to such low steady-state post-harvest basal areas that these legal restrictions are violated. In the case of Norway spruce, the steady-state basal area deviations from the legal limits remain minor (articles **I** and **II**), implying that the costs from fulfilling the legal restrictions remain minor as well. In contrast, in pure Scots pine stands, to gain enough ingrowth for continuous cover forestry, the basal area must be kept at a much lower level. This produces a clear conflict between the maximization of timber revenues and the current forest legislation.

While Scots pine favours rotation forestry (articles **I** and **II**), the harsh climate with decreased growth conditions favour continuous cover forestry (Tahvonen and Rämö 2016). In article **III,** we study Scots pine stands in the harsh climate of upper Lapland in northernmost Finland. Despite the relatively low continuous cover favourability of Scots pine (articles **I** and **II**), continuous cover forestry emerges as a valid management also for Scots pine under decreased growth conditions (**III**). Furthermore, considering non-timber ecosystem services, such as the negative externalities of forestry on reindeer husbandry increase the favourability of continuous cover forestry (article **III**).

Continuous cover forestry is argued to have relatively high multifunctional properties compared to rotation forestry (EASAC, 2017; Assmuth et al. 2018; Filyushkina et al. 2018, Peura et al. 2018; Tahvonen et al. 2019). Similarly, mixed-species stands are argued to produce higher levels of non-timber ecosystem services compared to a single-species stands (Gamfeldt et al. 2013; Felton et al. 2016; Olsson et al. 2019). Thus, the inclusion of non-timber ecosystem services and biodiversity values into the optimization problem would favour heterogenous mixed-species continuous cover forestry relative to homogenous single-species rotation forestry.

4.2 The effect of ecological growth models

Rotation forestry and maximum sustainable yield-oriented forest policy of post-WW2 era Finland had long-lasting consequences on Finnish forest sciences and especially on the development of continuous cover forestry (Jalonen et al. 2006). This becomes evident when considering the low number of Finnish ecological models suitable for both rotation forestry and continuous cover forestry, i.e. the models in Pukkala et al. (2011, 2013). This low number of ecological models is potentially problematic, as optimization is a powerful tool in uncovering any model “loopholes” and unrealistic ecological models may result in unrealistic optimization outcomes. Thus, economic-ecological optimization assigns a lot of weight to the reliability of the ecological models used.

Ecological models have a strong effect on the economically optimal solutions, most notably due to differences in models describing ingrowth (article **I**). The ecological models applied in this dissertation (i.e. models by Bollandsås et al. 2008 and Pukkala et al. 2011, 2013) use rather simplistic model forms for ingrowth. For example, the models omit differences in seed production capabilities between different-sized trees (cf. Nygren et al. 2017). In the economically optimal continuous cover forestry solution steady states, the basal area is typically decreased by thinning from above in a way that allows enough ingrowth for the continuation of continuous cover forestry. As a result, especially in pure Scots pine stands (articles **I**–**III**), the economically optimal post-harvest basal area may be extremely low and the residual stand may consist of very small-sized trees. Thus, if a stand cannot rely on seed material from nearby stands, continuous harvesting from above could potentially lead to a shortage of seed material in the long run. Such problems with size-structured models could be avoided by applying ingrowth models based on the number of trees per species per size class (see Getz and Haight 1989, p. 247–248).

It should be kept in mind that the stand state and development in this dissertation (articles **I**–**III**) is described with a size-structured transition matrix model (Leslie 1945; Usher 1966, 1969) based on diameter breast height. The even distribution of trees within size classes and within a stand is an underlying assumption in size-structured models. Thus, optimal thinning in size-structured models must be understood to be spatially evenly distributed within a stand. Other continuous cover forestry thinning methods also exist, e.g. the creation of small gaps. Studying e.g. small-gap creation would ideally require an individual-tree distance-dependent model that also includes data of tree coordinates. The downside of increasing the detail level of a model is that it simultaneously increases the complexity of optimization. This may result in extremely long computation times during optimization or difficulties in finding even local optimums. In addition, increased model detail may complicate the interpretation of the optimal solutions.

4.3 Economics of thinning

Historically, the realistic inclusion of thinnings in economic optimization models has proved difficult. Forest economics has therefore traditionally omitted thinnings and favoured simplified analytically solvable univariate optimization models, i.e. the Samuelsson (1976) version of the Faustmann (1849) model (see e.g. Amacher et al. 2009). However, as thinning is the main method for controlling stand development, omitting thinning is a notable simplification. In this dissertation (articles **I**–**III**), we optimize both the timing and intensities of thinnings. As the thinning timing variables are binary, while the thinning intensity variables are continuous, the optimization problem becomes a computationally time-consuming mixed-integer nonlinear optimization problem.

Currently, thinning from below is the most applied thinning method in Finland, and it is still recommended for all thinning scenarios in the Finnish silvicultural recommendations (Äijälä 2019, p. 147). The idea in thinning from below is that it increases the growth of the remaining large trees and helps them to reach a predetermined clearcut size earlier. However, increasing the growth of the remaining large trees does not guarantee economic efficiency and thinning from below makes continuous cover forestry infeasible. In addition, the level of timber yield of a thinning strategy does not reveal its economic profitability (article **II**). A common result in forest economic studies with optimized thinning is that in both rotation and continuous cover forestry, thinnings are aimed at sawlog-sized trees by thinning from above (Haight 1985, Hyytiäinen et al. 2004, Pukkala et al. 2010, Niinimäki et al. 2012, Tahvonen et al. 2013, Tahvonen and Rämö 2016). In this dissertation (articles **I**–**III**), all economically optimal thinnings are made from above. According to the detailed harvesting costs model by Nurminen et al. (2006) (articles **I**–**III**), it is less costly per cubic metre to harvest large trees compared to small trees. Furthermore, the applied ecological models for diameter growth (Bollandsås et al. 2008; Pukkala et al. 2013) include asymmetric competition via basal area. The asymmetric competition module causes the growth of small trees to respond more to the removal of large trees than vice versa. As a result, economically optimal thinning is a result of multiple factors and is characterized by the removal of large-diameter trees that have passed their relative peak value growth, are cheap to harvest cubic metre-wise, and take up growing space from smaller trees.

In continuous cover forestry, revenues come solely from thinnings, while in rotation forestry thinnings may still produce a significant proportion of the revenues. In article **II,** we demonstrate that omitting optimal thinnings and only optimizing the rotation length, i.e. applying the Samuelsson (1976) model causes significant economic losses. Furthermore, the presence of a naturally regenerating tree species with low or non-commercial value, such as Eurasian aspen, and high interest rate increase the economic significance of thinning. In article **III,** we study conventional forest management based on thinning from below. We demonstrate that omitting thinning from below and optimizing only for rotation length produce a higher profitability than conventional forest management. Thus, thinning has a fundamental economic role in both boreal and arctic forestry and can significantly increase (when done optimally) or decrease (when done non-optimally) the profitability of timber production (articles **II** and **III**). According to the results of this dissertation (articles **I**–**III**), thinning from above can be considered an economically valid thinning strategy for all commercially significant Fennoscandian tree species, independent of the optimal management regime. This is in sharp contrast with the current silvicultural recommendations promoting thinning from below (Äijälä 2019, p. 147).

Before the implementation of the most recent Finnish forest act (1085/2013) and Forest decree (1308/2013) at the beginning of 2014, continuous cover forestry was made practically infeasible in Finland through a set of strict restrictions on forest management. This "ban" of continuous cover forestry dates to the post-WW2 era, when the state of Finnish forests caused concerns due to increased harvesting targets (Jalonen et al. 2006). Historically, before the mid-20th century, "high grading" selective harvesting of natural-origin forests for peasant household use was a common practice in Finland (Siiskonen 2007). Appelroth et al. (1948)

viewed this selective harvesting as “devastating” to Finnish forests. Thus, Appelroth et al. (1948) published a “declaration” condemning non-rotation forestry methods and listing the rotation forestry methods deemed appropriate. What followed was a centralized forest policy based on the maximum sustainable yield objective and an implementation of various rotation forestry methods with a set of strict restrictions (Kuuluvainen et al. 2012). Now, it is important to distinguish between “high grading” -type selective harvesting that took place in post-WW2 era Finland and thinnings in economically optimal continuous cover forestry. In “high grading”, only trees with an adequately high stumpage value are harvested, while post-harvest stand development is ignored. This form of shortsighted resource extraction can obviously occur in a Hardin (1968) -type “tragedy of commons” situations. However, following the economic reasoning by Faustmann (1849), the time horizon in forest economics should be infinitely long. Thus, in economically optimal continuous cover forestry, post-harvest stand development cannot be disregarded. In article **II,** we provide an example of the differences between “high grading” selective harvesting and economically optimal continuous cover forestry. We demonstrate that applying “high grading” results in decreased profitability, decreased yield, and in a completely different stand structure compared to economically optimal continuous cover forestry. Thus, “high grading” cannot be viewed as a legitimate argument against continuous cover forestry (cf. Nyland 1992 and Appelroth et al. 1948).

4.4 Policy implications

According to our results (article **II**), aiming for pure single-species stands through the active felling of naturally regenerating other native tree species is clearly not optimal. In contrast, aiming for a mixed-species stand with tree species of contrasting shade tolerances may be considered a valid management strategy (article **II**). In addition, our results clearly show that thinning from above is an economically superior harvesting strategy (articles **I**–**III**). Thus, silvicultural guidelines should consider promoting mixed-species continuous cover forestry and thinning from above.

Forestlands in upper Lapland are mainly government owned and managed while the land area is simultaneously legally designated as the homeland of the Sámi people. Finnish legislation requires that forestry in Sámi peoples’ homeland regions does not cause considerable negative externalities on reindeer herding, which is an integral part of the Sámi peoples’ culture (Reindeer Husbandry Act 848/1990). In article **III**, we demonstrate that the profitability of industrial timber production in the Sámi peoples’ homeland region in upper Lapland is low. In addition, considering the carbon sequestration properties of forests and the negative externalities of forestry on reindeer husbandry, the economic rationality of commercial timber production in the area becomes questionable. In addition, as an EU member state, Finland must abide to LULUCF regulations that limit the net carbon emissions from land use including forests. According to our results, continuous cover forestry offers a possible socially preferable option to integrating timber production and non-timber ecosystem services (e.g. carbon storage and maintenance of reindeer pasturelands) in the Sámi peoples’ homeland region.

4.5 Future research directions

Most of the economic research on continuous cover forestry has relied on statistical-empirical size-structured ecological models. While these models include the most practically essential information on forest management, they still leave many aspects of forest management uncovered, e.g. sawlog quality formation. Thus, the economic research on continuous cover forestry would gain from applying more complex ecological models under the limitations set by computer technology and optimization algorithms. A natural next step from the size-structured model used in this dissertation (articles **I**–**III**) would be a single tree model. Since in transition matrix model a proportion of trees always moves to the next size class, forest growth and thus the profitability of forestry can be overestimated (see Picard and Liang 2014). Since low profitability favours continuous cover forestry, applying a single tree model would likely favour continuous cover forestry compared to the transition matrix model.

A large proportion of Finnish peatlands have been drained for timber production and the future of these drained peatlands is under debate. Currently, forest management in drained peatlands has focused on rotation forestry and stand drainage by ditching. However, these practices produce sediment, nutrient, and carbon releases to the receiving waterbodies (Nieminen et al. 2018), thus causing e.g. decreases in water quality. However, if optimally managed, the standing trees in continuous cover forestry could provide enough drainage to substitute ditching (Sarkkola et al. 2010, 2012). The economic models developed and used in this dissertation should be expanded to cover peatlands.

In article **III**, we simultaneously optimize timber production and carbon storage in a pure Scots pine stand. Carbon pools in article **III** consist of carbon from living tree biomass, dead tree matter, and end products. However, forestry operations, such as harvester movement and soil preparation, cause changes to forest soil. Also, high stand volumes imply high litter inputs from living trees into the soil. Thus, forestry also has a direct impact on soil carbon. Including soil carbon is a natural step to expanding the economic optimization model of article **III**. Including soil carbon into the model would likely favour continuous cover forestry due to the avoided soil carbon releases following regeneration fellings. However, the magnitude of this favourability remains unanswered.

In article **III,** we present a novel dynamic economic approach for analyzing old-growth forest conversions to forestry, where the emphasis is on the co-production of timber and carbon storage (cf. Fargione et al. 2008). Given the economic parameters for timber prices, carbon price, and interest rate, our approach can determine whether such land conversions are economically optimal or not. Furthermore, our approach is fully flexible to be used in any geographical location. Thus, the calculations on old-growth conversions in article **III** should be expanded to cover geographical locations also outside the upper Lapland region.

Lastly, the results of this dissertation are based on deterministic models for forest dynamics and constant economic parameters. However, societies and ecosystems are in constant change. Studying the impacts of these changes and the uncertainties included requires inclusion of stochasticity in the ecological models and economic parameters.

5 CONCLUSIONS

Forest economics is a highly interdisciplinary field of science that combines economics and ecology. This dissertation applies economic-ecological optimization where economic optimization models are coupled with species-specific ecological models for forest dynamics, i.e. how trees grow, die, and naturally regenerate. The models and methods developed in this dissertation have served a direct practical purpose, being partly used in the most recent Finnish silvicultural guidelines for continuous cover forestry (Sved and Koistinen 2019, p. 76–80). The three articles of this dissertation expand the existing literature covering both continuous cover and rotation forestry. Article **I** concentrates on studying differences in the continuous cover favourability between pure Norway spruce and Scots pine stands and the effect of ecological models on the economically optimal solutions. In article **II,** optimization of the management regime is expanded to cover mixed-species stands. Finally, in article **III**, the optimization of the management regime is studied with a model that also includes non-timber ecosystem services, i.e. carbon storage and the negative effects of timber production to reindeer husbandry.

The main contribution of this dissertation is the systematic study of the economically optimal choice between continuous cover and rotation forestry, which covers the most economically significant Fennoscandian tree species, various ecological growth models, and a spectrum of economic parameters. This allows us to study and isolate the effects of the optimal solutions caused by tree species, ecological models, and economic parameters. According to the results of this dissertation (articles **I**–**III**), we conclude that continuous cover forestry, in many cases, appears to be a sound forest management strategy in both boreal and arctic forestry.

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