Optimizing continuous cover and rotation forestry in mixed-species boreal forests with Scots pine and silver birch

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Abstract

Boreal forests fulfil a myriad of ecological, social and economic functions in modern society, which is why it is crucial to manage them in the best way possible. The prevailing forest management strategy in Finland has been rotation forestry, but a Finnish citizens' initiative and the new EU forest strategy for 2030 have for ecological reasons been calling for a reduction in clearcuts and a switch to continuous cover forestry. While a growing number of economic-ecological optimization studies illustrate the economic aspects of optimal management regime choice in Nordic conditions, the understanding remains incomplete. To contribute to this line of research, this thesis studies the economically optimal management regime and species composition of mixed-species boreal forests with a previously unexamined species combination: Scots pine (*Pinus sylvestris* L.) and silver birch (*Betula pendula* Roth).

The analysis is based on a theoretically sound and generalized stand-level economic-ecological model that maximizes the net present value of forestry income. In this setup, the optimal management regime is determined endogenously and flexibly, by dynamically optimizing both the rotation period and the timing and intensity of thinnings in a tri-level structure. All model details are empirically estimated. Forest stand development is described by size-structured empirical growth models by Pukkala et al. (2011, 2013) and by Pukkala et al. (2021), of which the latter has not been used in this line of analysis before.

The results of this thesis show, for the first time empirically, that it can be economically optimal to conduct near-clearcuts without investing in artificial regeneration afterwards. Near-clearcuts create favourable conditions for utilizing the unharvested young trees and natural regeneration of pioneer species in generating a new tree cohort. This management strategy is found to be suitable for birch-dominated pine–birch stands with a 1% interest rate, as well as pure birch stands. With a 3% interest rate, continuous cover forestry becomes optimal for mixed stands. A further outcome of this thesis is that continuous cover management of pure pine stands is found to be more viable than in previous optimization studies. Further, it is shown that it is economically beneficial to let birch regenerate in a pine stand and even dominate it, due to improvements in overall ingrowth. The characteristics of the optimal solutions are, however, dependent on the ecological growth model used.

In light of the cases studied in this thesis, neither rotation forestry nor continuous cover forestry is categorically superior in terms of timber income. There are demonstrably many cases where taking advantage of the environmental benefits of continuous cover forestry and higher tree species diversity is optimal also with respect solely to maximizing timber revenues.

Keywords

Forest management, forest policy, management regimes, rotation forestry, continuous cover forestry, optimal harvesting, optimal rotation, dynamic optimization, mixed-species stands, Scots pine, silver birch

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Tiivistelmä

Boreaalisen vyöhykkeen metsillä on lukuisia ekologisia, sosiaalisia ja taloudellisia merkityksiä modernissa yhteiskunnassa, minkä vuoksi niitä on pyrittävä hoitamaan parhaalla mahdollisella tavalla. Jaksollinen kasvatus on ollut Suomessa pitkään vallitseva metsänhoitomenetelmä, mutta suomalainen kansalaisaloite ja EU:n uusi metsästrategia 2030 ovat vastikään ekologisiin syihin vedoten vaatineet avohakkuiden vähentämistä sekä jatkuvapeitteiseen kasvatukseen siirtymistä. Vaikka optimaalisen metsänhoitomenetelmän valintaa pohjoismaisissa olosuhteissa sekä valintaan liittyviä taloudellisia näkökulmia on taloudellis-ekologisissa optimointitutkimuksissa alettu kuvata yhä enemmän, on ymmärrys kyseisestä aiheesta vielä vaillinaista. Tämä tutkielma tarkastelee taloudellisesti optimaalisen metsänhoitomenetelmän valintaa ja optimaalista puulajikoostumusta boreaalisissa sekametsissä. Tutkimuksen kohteena on metsämännyn (*Pinus sylvestris* L.) ja rauduskoivun (*Betula pendula* Roth) puulajiyhdistelmä, jota ei taloudellisesti optimaalisen metsänhoitomenetelmän kannalta ole aiemmin tarkasteltu.

Analyysi perustuu teoreettisesti johdonmukaiseen ja yleiseen taloudellis-ekologiseen malliin, jossa metsänhoidon tulojen nettonykyarvoa maksimoidaan metsikkötasolla. Tässä asetelmassa optimaalinen metsänhoitomenetelmä määrittyy mallin sisällä, kun kiertoaikaa sekä harvennusten ajoitusta ja intensiteettiä optimoidaan dynaamisesti. Mallin kaikki yksityiskohdat on estimoitu empiirisesti. Metsän kehitystä kuvataan Pukkalan tutkimusryhmineen (2011, 2013, 2021) estimoimilla kokoluokkarakenteisilla empiirisillä kasvumalleilla. Malleista uusinta ei aikaisemmin ole käytetty metsänhoidon dynaamiseen optimointiin.

Tutkielman tulokset osoittavat ensimmäistä kertaa empiirisesti, että taloudellisesti voi olla optimaalista tehdä melkein-avohakkuita ilman, että metsikköä niiden jälkeen uudistetaan keinollisesti. Melkein-avohakkuut luovat suotuisat olosuhteet korjaamatta jätetyn nuoren puuston ja pioneerilajien luontaisen uudistumisen hyödyntämiselle uuden puukohortin synnyttämisessä. Kyseinen metsänhoitostrategia sopii paitsi koivikoille, myös koivuvaltaisille mänty-koivusekametsille korkokannan ollessa 1 %. Sen sijaan 3 %:n korkokannalla jatkuvapeitteisestä kasvatuksesta tulee sekametsissä optimaalista. Tutkielman tulosten perusteella jatkuvapeitteinen kasvatus sopii männiköille paremmin kuin edeltävät optimointitutkimukset ovat esittäneet. Lisäksi tulokset osoittavat, että taloudelliselta kannalta koivun kannattaa antaa uusiutua mäntymetsikössä ja levitä jopa metsikön valtapuuksi, sillä tämän seurauksena metsikön luontainen uudistuminen voimistuu. Optimiratkaisuiden yksityiskohdat riippuvat optimoinnissa käytetyistä ekologisista kasvumalleista.

Tutkielmassa tarkasteltujen tapausten valossa ei voida sanoa jaksollisen tai jatkuvapeitteisen kasvatuksen olevan puuntuotannon tulojen kannalta kategorisesti toistaan parempi menetelmä. Monissa tapauksissa jatkuvapeitteisen kasvatuksen ja monimuotoisemman puulajivalikoiman hyödyntäminen ympäristöetujen saavuttamiseksi on optimaalista jo pelkästään hakkuutulojen maksimoinnin kannalta.

Avainsanat

Metsänhoito, metsäpolitiikka, metsänhoidon menetelmät, jaksollinen kasvatus, jatkuvapeitteinen kasvatus, optimaalinen puunkorjuu, optimikiertoaika, dynaaminen optimointi, sekametsät, metsämänty, rauduskoivu

Ohjaaja tai ohjaajat

Olli Tahvonen, Vesa-Pekka Parkatti ja Nico Österberg

Säilytyspaikka

Viikin Tiedekirjasto

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1 Introduction

Forests fulfil a myriad of functions in the 21st century world. Not only are forests a source of timber income for forest owners and a source of raw material for the forest industry, but they also provide non-market values through ecologically, socially and culturally important ecosystem services (Brockerhoff et al., 2017). Forests have a central role in solving some of the greatest ecological crises of our time. All mitigation pathways for achieving the Paris Agreement target of limiting global warming to 1.5 °C from pre-industrial levels rely, to varying extents, on carbon dioxide removal and associated changes in land use (IPCC, 2018). A land-sector roadmap of priority measures for achieving this target shows that improving forest management (for instance, by optimizing rotation lengths) is an important strategy for increasing carbon removals in the EU area (Roe et al., 2019). In Finland, forestry-related changes in forest habitats are a major reason for species endangerment (Hyvärinen et al., 2019). Indeed, forests are also crucial for stopping global biodiversity loss (Dasgupta, 2021).

Finland is a particularly forest-rich country, with approximately 75% of its total land area covered with forests, and the state owning 35% of all forestry land (Peltola et al., 2019). The prevailing forest management strategy – just like in other Nordic countries – has been rotation forestry (RF) (Mason et al., 2021). In rotation forestry, a final felling (such as a clearcut) is carried out at the end of each rotation, after potential thinnings. Clearcutting is the process of harvesting the forest to the extent that the treatment area turns into an open area. The forest is usually then regenerated artificially. As a consequence, the size of the trees is roughly even all throughout the rotation. This management regime has historically been promoted by Finnish forest policy, in order to provide a sustainable supply of raw material for forest industries (Kuuluvainen et al., 2012).

A relevant alternative for rotation forestry in boreal conditions is continuous cover forestry (CCF). In this management strategy, the forest remains covered at all times. Repeated partial harvests (such as thinnings from above, in which the largest trees are removed) are carried out in a way that promotes the growth of the remaining tree stock and the natural development of new seedling material. Hence, the forest regenerates naturally. Continuous cover forestry became a permissible management regime in Finland in 2014, when the Finnish Forest Act (1996/1093; FINLEX, 1996) was reviewed and the restrictions prohibiting this regime were removed. Consequently, private and public forest owners were granted the freedom to decide between RF and CCF unrestricted. Despite this, the share of CCF harvests out of overall harvests was still only a few percent in 2018 (Kniivilä et al., 2020).

The issue of forest management regimes was once again brought into the Finnish public debate in 2018, when a citizens' initiative called for a prohibition of clearcuts and a transition to the methods of continuous cover forestry in state-owned forests (Parliament of Finland, 2019). The initiative underlined the importance of accounting for other ecosystem services in forestry aside from timber production: the bill was justified by emphasizing the superiority of CCF over RF in providing these ecosystem services and in reducing many negative environmental impacts of forestry. Further, the initiative also argued that switching to continuous cover forestry is often economically profitable. In October 2021, the Finnish Agriculture and Forestry Committee opted to reject the bill but proposed that Parliament would diversify the management strategies in state-owned forests by increasing the share of CCF (Agriculture and Forestry Committee, 2021).

Recently, forest management regimes have also been discussed on the EU level in the context of the EU taxonomy for sustainable activities. The EU taxonomy is a classification system that provides definitions for environmentally sustainable economic activities, in order to help direct more finance to sustainable projects and practices across the EU (European Parliament, 2020). In the proposed technical criteria for listing climate sustainable forestry activities, the Commission called for the promotion of a concept termed "close to nature forestry" (European Commission, 2020). The concept was defined ambiguously, but in the public, it was interpreted to refer to continuous cover forestry, among other less intensive management practices. This struck fears of economic losses in forest-rich member states. As a result of their opposition, "close to nature forestry" was left out of the first delegated act on sustainable activities (approved in principle in April 2021), with the intention of the concept being revisited in the near future (European Commission, 2021a).

The EU has also recently taken a stance on forest management regimes in the new EU forest strategy for 2030 (European Commission, 2021b). The strategy gives reference points for sustainable forest management, in order to help the EU achieve its environmental objectives. Initially, the leaked draft strategy stated that clearcuts should be avoided whenever possible (Forest Defenders Alliance, 2021). Again, the idea of rotation forestry being defined as something to avoid was seen as an economic threat. By virtue of opposition by forest-rich member states, the statement in the final strategy (European Commission, 2021b) was watered down, noting that clearcuts "should be used only in duly justified cases".

Both the Finnish citizens' initiative and EU's recent stands on sustainable forestry practices raise the point that the choice between the two alternative management regimes, RF and CCF, has pronounced implications for the ecological and economic outcomes of forestry. In terms of environmental impacts, CCF has, for instance, been shown to support a higher level of carbon sequestration and biodiversity than RF (Díaz-Yáñez et al., 2020; Eyvindson et al., 2021). Other management choices besides the regime also have an impact on the environmental status of the forest. Stands with higher tree species diversity provide more ecosystem services (Gamfeldt et al., 2013) and are more resilient to new environmental conditions and disturbances, such as climate change, pests, and diseases (Gauthier et al., 2015). From an economic point of view, determining the optimal management regime is complicated due to the large number of factors affecting the optimal choice. While in recent years, economic-ecological research has drawn a clearer picture on the optimal regime choice in Nordic conditions, the understanding of the economic aspects in choosing the optimal regime remains incomplete.

The classic Faustmann (1849) model and the objective of maximizing revenues from forest ownership (that is, the net present value of timber revenues), has been the basis for economic models for forestry. In contrast to maximizing timber yield, this approach results in the economically optimal forest management solution and is also a reasonable starting point for determining socially optimal wood production, as long as the timber market is competitive (Samuelson, 1976). However, following Samuelson (1976), economic research on forestry has been focused on rotation forestry (with most models requiring clearcut by construction), while attempts to model continuous cover forestry have been few.

Most attempts to optimize continuous cover forestry have included strong simplifications or other constraints. A major simplification in past literature has been the application of a static optimization framework, commonly in the form of the "Investment efficient" approach, introduced by Adams (1976). This approach does not allow for any temporal fluctuations in management choices, even though optimizing forest management is a dynamic problem (Getz & Haight, 1989, pp. 287–295; Haight, 1985). In their seminal paper, Adams and Ek (1974) solve the transition path and continuous cover steady state separately using numerical nonlinear dynamic optimization. In Haight (1985) and Haight and Getz (1987), the optimization has been done in more general form. Haight and Monserud (1990) optimized the continuous cover management of mixed-species conifer stands in the Northern Rocky Mountains through the application of a dynamic model but still under several simplifications. These early contributions have been dismissed in most later studies. Wikström (2000) was the first attempt to dynamically optimize the harvest timings (rather than applying a fixed harvest interval) as well as intensities in uneven-aged Norway spruce stands, but the solution method applied other restrictive features. Tahvonen and Rämö (2016) optimized the management of boreal Norway spruce stands and were the first to optimize the harvest timing without applying other restrictive constraints.

Past profitability comparisons between RF and CCF have been based on separate, incompatible RF and CCF models. However, in order for the comparison to be sound, the two alternative management regimes have to be analysed with the same model. Following Haight and Monserud (1990), Tahvonen et al. (2010) compared the profitability of RF and CCF in Norway spruce stands by using various initial states (representing continuous cover steady states) to compute whether it is optimal to clear-cut, in which case RF is optimal, or to continue with continuous cover, in which case CCF is optimal. However, despite the pioneering nature of the contributions by Haight and Monserud (1990) and Tahvonen et al. (2010), this approach was not theoretically sound for optimizing the choice between RF and CCF; the foundations for such a setup were later laid in Tahvonen (2015, 2016) and Tahvonen and Rämö (2016). Their model simultaneously covers RF and CCF as special cases and potentially optimal regimes. It determines the optimal regime (alongside other management decisions, including harvest timing) endogenously and flexibly via dynamic optimization, in an empirically detailed and generalized setup. This model has been applied numerically to study the economically optimal regime choice in boreal Norway spruce stands (Parkatti et al., 2019; Tahvonen & Rämö, 2016), Scots pine stands (Parkatti et al., 2019) and mixed-species forests (Parkatti & Tahvonen, 2020).

CCF often generates smaller timber yields than RF, and the harvesting of trees is more expensive (Parkatti & Tahvonen, 2020; Tahvonen, 2011; Tahvonen & Rämö, 2016). On the other hand, CCF implies avoided investments in artificial regeneration, a steadier flow of income, and higher shares of valuable sawtimber in the harvested stock (Tahvonen & Rämö, 2016). Previous research outcomes indicate that CCF is profitable in boreal Norway spruce stands and mixed-species stands, especially with higher interest rates and higher regeneration costs (Parkatti et al., 2019; Parkatti & Tahvonen, 2020). Dynamic economic-ecological optimization has not supported continuous cover management of boreal Scots pine stands (Parkatti et al., 2019; Parkatti & Tahvonen, 2020).

This thesis follows the line of economic-ecological optimization literature described above by economically optimizing the management of mixed-species boreal stands with a previously unexamined species combination of Scots pine (*Pinus sylvestris* L.) and silver birch (*Betula pendula* Roth). From here on, these species will mostly be referred to as pine and birch for simplicity. Birch is an early successional and light-demanding pioneer species that often occurs in coniferous forest stands (Hynynen et al., 2010). Both pine and birch are commercially significant tree species in

Finland (Peltola et al., 2019). Previously, this species combination has only been studied in even-aged stands by Valsta (1986), who used a whole stand model and dynamic programming to optimize harvest timings, harvest intensities and species proportions but not the choice between RF and CCF. Further, this thesis utilizes a new ecological forest growth model by Pukkala et al. (2021), which has not been used in this line of analysis before, alongside an older model by Pukkala et al. (2011, 2013). The Pukkala et al. (2021) model is based on a data set with better geographic coverage and also includes the recent effects of climate change and nitrogen deposition on forest growth. In addition to the mixed-species case, solutions are also computed for single-species Scots pine and silver birch stands in order to test the behaviour of the ecological models and to better understand the impacts of species characteristics on the optimal solutions.

To be precise, this thesis aims at answering the following research questions:

1. *Which is the economically optimal management regime for boreal mixed-species stands with Scots pine and silver birch: rotation forestry or continuous cover forestry?*

2. *Are there economic benefits in growing silver birch in a Scots pine stand? If yes, what are the optimal species proportions in the pine–birch mixture?*

3. *The Finnish citizens' initiative (Parliament of Finland, 2019) and the new EU forest strategy for 2030 (European Commission, 2021b) have both underlined a desire to avoid clearcuts in forestry. With respect solely to timber revenue in pine–birch stands, is this objective supported by economic-ecological optimization?*

Given the numerous ecological, social and economic functions that forests fulfil in modern society, alongside the manifold impacts of management choices on the ecological and economic outcomes of forestry, it is crucial to ensure that our finite forest resources are being managed in the best way possible. This requires economic reasoning, in which regard a sensible starting point is understanding the profitability of timber production. By answering the aforementioned research questions, this thesis contributes to the current understanding of the optimal regime and other management choices in Nordic conditions, in the sole context of timber revenue.

2 Models and methods

2.1 Optimization problem and economic parameter values

Following Parkatti and Tahvonen (2020), denote the number of trees of species j in size class s, at the beginning of time period t, by x_{jst} $(j=1,...,l; s=1,...,n;\ t=t_0,t_0+1,...,T)$. The stand state at any moment of time t is given as

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

Natural regeneration of species j is given by the ingrowth function $\phi_j(\mathbf{x}_t)$. The fraction of trees of species j that move to the next size class during each period t is given as $0 \le \alpha_{js}(\mathbf{x}_t) \le 1 (j=1,...,l; s=1,...,n-1)$. The fraction of trees of species j in each size class s that die during period t equals $0 \le \mu_{js}(\mathbf{x}_t) \le 1 (j=1,...,l; s=1,...,n)$. Therefore, $1-\alpha_{js}(\mathbf{x}_t)-\mu_{js}(\mathbf{x}_t) \ge 0$ gives the fraction of trees of species j that remain in the same size class during period t. Let $h_{jst}, (j=1,...,l; s=1,...,n; t=t_0,t_0+1,...,T)$ denote the trees of species j that are harvested from each size class s at the end of period t. Thus, total harvests at the end of each period are given as

$$\mathbf{h}_t = \begin{pmatrix} h_{11t} & h_{12t} & \cdots & h_{1nt} \\ h_{21t} & h_{22t} & \cdots & h_{2nt} \\ \vdots & \vdots & \ddots & \vdots \\ h_{l1t} & h_{l2t} & \cdots & h_{lnt} \end{pmatrix}.$$

Let harvesting revenues for clearcut and thinning be denoted by $R(\mathbf{x}_T)$ and $R(\mathbf{h}_t)$, respectively, and denote the variable harvesting costs for clearcut (cl) and thinning (th) by $C_{cl}(\mathbf{x}_T)$ and $C_{th}(\mathbf{h}_t)$, respectively. An additional fixed harvesting cost C_f originates from planning the harvest operations and transporting the logging machinery to the site. The cost of artificial regeneration is given as $w \ge 0$, indicating the net present value of the costs from all artificial regeneration operations (ground mounding, planting and tending of the seedling stand) on the stand at different points of time. Following the realistic estimates by the Natural Resources Institute Finland (2014), the cost is set to

€1489·ha[-1] when the interest rate equals 1% and to €1401·ha[-1] when the interest rate equals 3%. All the aforementioned costs and revenues are given in €·ha[-1]. The discrete time discount factor is given by $b^{\Delta} = 1/(1+r)^{\Delta}$, where r is the annual interest rate and Δ indicates the time period length (five years). Accounting for fixed harvesting costs in the optimization implies that harvesting may not be performed in every period. Therefore, we use the binary variables $\delta_t : Z \in \{0,1\} \, (t = t_0, t_0+1, ..., T)$ and define harvests and fixed harvesting costs by Boolean operators: $h_{jst} = \delta_t h_{jst}$ and $\delta_t C_f$, respectively. Consequently, $\delta_t = 0$ implies that harvesting equals zero at period t, and the fixed harvesting cost does not occur. Similarly, $\delta_t = 1$ implies that the fixed harvesting cost occurs and harvesting intensity $h_{st} \geq 0 \, (s = 1, ..., n)$ is freely optimized. Let J denote the bare land value (BLV; the net present value of a hectare of bare forest land). The economic optimization problem can be written as

$$J(\mathbf{x}_{t_0}, T) = \max_{\{h_{jst}, \delta_t, t=t_0,...,T, T\in[t_0,\infty)\}} \frac{-w + \sum_{t=t_0}^{T-1} [R(\mathbf{h}_t) - C_{th}(\mathbf{h}_t) - \delta_t C_f] b^{\Delta(t+1)} + [R(\mathbf{x}_T) - C_{cl}(\mathbf{x}_T) - \delta_T C_f] b^{\Delta(T+1)}}{1 - b^{\Delta(T+1)}} \tag{1}$$

subject to

$$x_{j,1,t+1} = \phi_j(\mathbf{x}_t) + [1 - \alpha_{j1}(\mathbf{x}_t) - \mu_{j1}(\mathbf{x}_t)] x_{j1t} - h_{j1t}, \quad j = 1, ..., l, \quad t = t_0, ..., T \tag{2}$$

$$x_{j,s+1,t+1} = \alpha_{js}(\mathbf{x}_t) x_{jst} + [1 - \alpha_{j,s+1}(\mathbf{x}_t) - \mu_{j,s+1}(\mathbf{x}_t)] x_{j,s+1,t} - h_{j,s+1,t}, \quad j = 1, ..., l, \quad s = 1, ..., n-1, \quad t = t_0, ..., T \tag{3}$$

$$h_{jst} = \delta_t h_{jst}, \quad j = 1, ..., l, \quad s = 2, ..., n, \quad t = t_0, ..., T \tag{4}$$

$$\mathbf{x}_{jst_0} \; given, \quad j = 1, ..., l, \quad s = 1, ..., n \tag{5}$$

Additionally, $\delta_t : Z \in \{0,1\}$, $x_{jst} \geq 0$ and $h_{jst} \geq 0 \, (j = 1, ..., l; s = 1, ..., n; t = t_0, ..., T)$.

Verbally, the aim of the empirical analysis is to numerically solve a dynamic economic model (1)-(5). The model describes forestry in size-structured mixed-species boreal forests, includes ecological tree species interaction and maximizes the net present value of forestry income over an infinite time horizon. The model is solved by dynamic optimization and the choice of management regime is endogenously determined by optimizing the rotation period and the timing and intensity of thinnings. No restrictions are posed on the steady-state stand structure nor the transition period (approach path) toward the steady state. Hence, the choice between RF and CCF can be optimized with no ad-hoc constraints and optimal solutions can be obtained from any initial state. The objective functional (1) includes a possibility of an infinitely long optimal rotation period (in other words, thinning forever without ever clear-cutting). The optimal management regime is therefore determined by the optimal rotation length *T*: a finite optimal rotation implies RF, which is defined as a solution where clearcuts are conducted. On the other hand, an infinitely long optimal rotation *T* implies CCF, which is defined as a solution where no clearcuts are conducted. In this case, no optimal rotation length and no optimal RF solution exists; the objective value increases as the rotation period increases.

Trees are divided into 11 discrete size classes. The size classes $s = 1,\ldots,11$ are categorized by mean diameter d_s (midpoint) that is measured at breast height, in 5-cm intervals from 2.5 cm to 52.5 cm. As the initial state is bare land, planted trees grow during the tending of the seedling stand. Hence, it is assumed that artificially regenerated trees enter the second size class of 7.5 cm after a delay, t_0, of 20 years. It is also assumed that the smallest size class $s = 1$ cannot be harvested in thinnings, which is why t_0 is also when the optimization begins. The initial state at t_0 will be denoted as $\mathbf{x}_{jst_0} = [x_{12t_0}, x_{22t_0}]$, where x_{12t_0} is the number of planted pine trees in second size class and x_{22t_0} is the number of naturally regenerated birch trees in second size class.

Species-specific timber prices are specified separately for sawlog p_{1j} and pulpwood p_{2j}. The roadside prices for sawlog and pulpwood are set at €58.65·m^{-3} and €30.51·m^{-3} for Scots pine, respectively. For birch, the roadside prices for sawlog and pulpwood are set at €49.73·m^{-3} and €30.50·m^{-3}, respectively. Each tree species has specific, size class -dependent sawtimber v_{1sj} (m^3) and pulpwood v_{2sj} (m^3) volumes, calculated according to Appendix 1. The gross revenues for each period can now be written as

$$R(\mathbf{h}_t) = \sum_{j=1}^{l} \sum_{s=2}^{n} (p_{1j} v_{1sj} + p_{2j} v_{2sj}) h_{sjt} . \tag{6}$$

The fixed harvesting cost C_f is set at €500·ha^{-1}. The variable harvesting costs are derived from the empirically estimated model by Nurminen et al. (2006) that describes time consumption of harvesting and hauling with modern harvesting machinery in Finnish conditions. The harvesting and hauling costs for clearcut ($i = cl$) and thinning ($i = th$) are given as

$$C_i = C_{ji0}\sum_{j=1}^{l}\sum_{s=2}^{n} h_{js}(C_{ji1} + C_{ji2}v_{sj} - C_{ji3}v_{sj}^2) + C_{i4}\sum_{j=1}^{l}\sum_{s=2}^{n} h_{js}v_{sj} + C_{i5}(\sum_{j=1}^{l}\sum_{s=2}^{n} h_{js}v_{sj})^{0.7} \quad i = th, cl, \tag{7}$$

where $v_{sj} = v_{1sj} + v_{2sj}$ gives the tree volume and the parameters $C_{jig}(j = 1,...,l; i = th, cl; g = 0,...,3)$ and $C_{ig}(i = th, cl; g = 4,5)$ are given in Appendix 2. The model specification together with the parameter values gives increasing costs with decreasing stem size, and higher costs per harvested tree for thinnings than for clearcuts.

2.2 Ecological growth models

When carrying out economic optimization of forestry, ecological growth models are needed for describing forest stand growth. Previously, Nordic economic-ecological optimization studies on optimal regime choice have relied on the ecological models by Bollandsås et al. (2008) and Pukkala et al. (2011, 2013), which have been the only generally available growth models that have been able to describe forest stand dynamics both in RF and CCF regimes in Nordic conditions. This thesis utilizes two size-structured empirical growth models: the previously used models by Pukkala et al. (2011, 2013) as well as a new model by Pukkala et al. (2021). Computing the results with two different growth models allows for analysing whether the optimization results depend on the ecological models used.

The growth model by Pukkala et al. (2011) was estimated from long-term field experiment data, the model by Pukkala et al. (2013) from four empirical data sets (including the Finnish National Forest Inventory), and the model by Pukkala et al. (2021) from the Finnish National Forest Inventory data alone. The model sets include species-specific functions for ingrowth (that is, natural regeneration), diameter increment and natural mortality on a mesic *MT* (*Myrtillus*) forest site with mineral soil. In *MT* forest sites, wood quality issues can occur in pure pine stands if the density of the sapling stand is too low, but shading from birch can improve the pine wood quality (Hynynen et al., 2010; Äijälä et al., 2019). The functions describe how the modelled phenomena are impacted by tree size, stand structure, species interactions, competition, forest site, and other factors. Model characteristics are shown in Figures 1a-c.

Let $a_0,...,a_8$ and $b_0,...,b_7$ represent the species-specific regression coefficients for diameter increment, $a_9,...,a_{14}$ and $b_8,...,b_{14}$ for mortality, and $a_{15},...,a_{21}$ and $b_{15},...,b_{18}$ for ingrowth (Appendix 3). Diameter increment in the individual tree models is divided with the width of a size class, q (5 cm) (Bollandsås et al., 2008): $\alpha_{jst} = q^{-1}(I_{js}(\mathbf{x}_t))(j = 1,...,l; s = 1,...,n; t = 0,1,...)$, where $I_{js}(\mathbf{x}_t)$ represents diameter growth, j represents tree species, s represents size class, and t represents time (in 5-year periods). This way, the diameter increment model can be used in the transition matrix model. Setting q at 5 cm implies that each tree can grow a maximum of one size class in each period. The fraction of trees moving from size class s to the next class $s+1$ during the next 5-year period is given as

$$\alpha_{jst} = q^{-1}\exp\left(\begin{array}{l} a_{j0} + a_{j1}\sqrt{d_s} + a_{j2}d_s + a_{j3}\ln(\mathrm{TS}) + a_{j4}\ln(\beta(\mathbf{x}_t)) + a_{j5}\dfrac{\beta_{s,\mathrm{pine}}(\mathbf{x}_t)}{\sqrt{d_s+1}} + a_{j6}\dfrac{\beta_{s,\mathrm{birch}}(\mathbf{x}_t)}{\sqrt{d_s+1}} \\ +a_{j7}SD(\mathbf{x}_t) + a_{j8}d_sSD(\mathbf{x}_t) \end{array}\right), \quad (8)$$

$$\alpha_{jst} = q^{-1}\exp\left(\begin{array}{l} b_{j0} + b_{j1}\sqrt{d_s} + b_{j2}d_s + b_{j3}\ln(\mathrm{TS}) + b_{j4}\ln(\beta(\mathbf{x}_t)+1) + b_{j5}\dfrac{\beta_s(\mathbf{x}_t)}{\sqrt{d_s+1}} + b_{j6}\dfrac{\beta_{s,\mathrm{birch}}(\mathbf{x}_t)}{\sqrt{d_s+1}} \\ +b_{j7}d_s Pendula \end{array}\right), \quad (9)$$

where (8) is the Pukkala et al. (2013) specification and (9) is the Pukkala et al. (2021) specification. Diameter at breast height (cm) is given by d. The total stand basal area ($m^2 \cdot ha^{-1}$) represents the sum of the surface areas (measured horizontally on the breast height) of the trees in the stand, and is given by the function $\beta(\mathbf{x}_t)$. The function is defined as $\beta(\mathbf{x}_t) = \sum_{j=1}^{l}\sum_{s=1}^{n}\gamma_{js}x_{jst}$ and $\beta_s(\mathbf{x}_t) = \sum_{j=1}^{l}\gamma_{js}\frac{1}{2}x_{jst} + \sum_{j=1}^{l}\sum_{i=s+1}^{n}\gamma_{ji}x_{jit} \quad (j = 1,...,l; s = 1,...,n-1)$, where γ_{js} is the basal area per tree of species j in size class s. Basal areas ($m^2 \cdot ha^{-1}$) of pine trees and birch trees larger than size class s (including half the trees in size class s) are hence given by $\beta_{s,\mathrm{pine}}(\mathbf{x}_t)$ and $\beta_{s,\mathrm{birch}}(\mathbf{x}_t)$, respectively – these variables indicate species influences on the diameter increment. $SD(\mathbf{x}_t)$ is the standard deviation of diameter (cm). Forest site is described by the temperature sum *TS* (degree days, set at 1100 d.d. for Central Finland or 1300 d.d. for Southern Finland). In the Pukkala et al. (2013) model, silver birch is the reference species for broadleaf species, whereas in the Pukkala et al. (2021) model, *Pendula* is an indicator variable for silver birch.

Generally, the maximum growth of both pine and birch is reached in the diameter range of 10–20 cm, and toward smaller and larger tree sizes the growth slows down (Figure 1a). The Pukkala et al. (2021) model generally predicts higher diameter increment than the Pukkala et al. (2013) model, except for the largest birch trees on a young stand. Birch benefits from being mixed with pine, in which case it grows faster than in a pure birch stand. Pine growth is fairly independent of competition with birch – in the Pukkala et al. (2013) model, birch has a slight disruptive effect. In the Pukkala et al. (2021) model, increasing the total basal area disrupts the growth of birch more and the growth of pine less than in the Pukkala et al. (2013) model. Increasing the temperature sum has a positive impact on diameter increment of both birch and pine. The impact is stronger in the Pukkala et al. (2021) model.

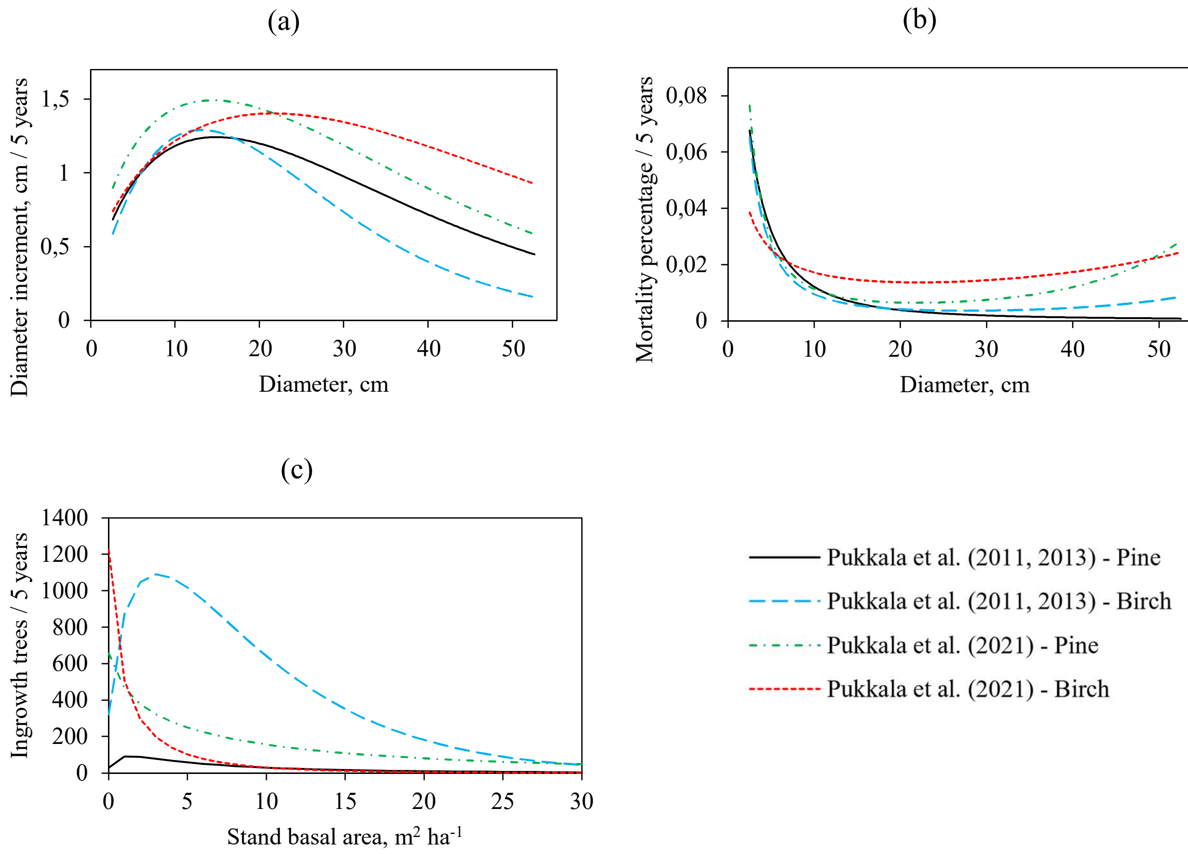

Figure 1a-c: Scots pine and silver birch diameter increment (a), mortality (b), and ingrowth (c) on a single-species stand with the Pukkala et al. (2011, 2013) and Pukkala et al. (2021) models. Note: Basal area in (a) equals 25 $m^2 \cdot ha^{-1}$. Basal area in larger trees in (a) and (b) equals 10 $m^2 \cdot ha^{-1}$.

The fraction of trees of species j in size class s that die during the next 5-year period is given as

$$\mu_{jst} = 1 - \begin{bmatrix} 1 + \exp(-a_{j9} - a_{j10}\sqrt{d_s} - a_{j11}d_s - a_{j12}\sqrt{\beta_{s,\text{pine}}(\mathbf{x}_t)} - a_{j13}\sqrt{\beta_{s,\text{birch}}(\mathbf{x}_t)} \\ -a_{j14}\sqrt{\beta_{s,\text{pine}}(\mathbf{x}_t) + \beta_{s,\text{birch}}(\mathbf{x}_t)}\,) \end{bmatrix}^{-1}, \tag{10}$$

$$\mu_{jst} = 1 - \begin{bmatrix} 1 + \exp(-b_{j8} - b_{j9}\sqrt{d_s} - b_{j10}d_s - b_{j11}\dfrac{\beta_s(\mathbf{x}_t)}{\sqrt{d_s + 1}} - b_{j12}\dfrac{\beta_{s,\text{pine}}(\mathbf{x}_t)}{\sqrt{d_s + 1}} - b_{j13}\dfrac{\beta_{s,\text{birch}}(\mathbf{x}_t)}{\sqrt{d_s + 1}} \\ -b_{j14}Birch) \end{bmatrix}^{-1}, \tag{11}$$

where equation (10) is by Pukkala et al. (2013) and (11) by Pukkala et al. (2021). *Birch* is a dummy variable for birch trees (*Betula* spp.). Mortality is relatively high for pine and moderate for birch. The mortality rates are especially high for small trees, but the survival rate rapidly improves as the trees grow (Figure 1b). While in the Pukkala et al. (2013) model mortality remains low with increasing diameter size, more trees start dying again toward large diameters in the Pukkala et al. (2021) model. The latter predicts lower mortality for small birch trees and higher mortality for larger birch trees. In the Pukkala et al. (2013) model, birch competition has a negligible impact on the survival of pine, whereas in the Pukkala et al. (2021) model birch survives slightly better in mixed pine–birch stands.

The amount of ingrowth of species j in the stand during the next 5-year period in the Pukkala et al. (2011, 2013) and in the Pukkala et al. (2021) models is given as

$$\phi_{jt} = \frac{\exp(a_{j15} + a_{j16}\sqrt{\beta(\mathbf{x}_t)} + a_{j17}\ln(\beta_{\text{birch}}(\mathbf{x}_t)) + a_{j18}\beta(\mathbf{x}_t))}{1 + \exp(-a_{j19} - a_{j20}\ln(\beta_j(\mathbf{x}_t)) - a_{j21}\sqrt{\beta_{\text{pine}}(\mathbf{x}_t)})}, \tag{12}$$

$$\phi_{jt} = \exp(b_{j15} + b_{j16}\ln(TS) + b_{j17}\sqrt{\beta(\mathbf{x}_t)} + b_{j18}\sqrt{\beta_{\text{pine}}(\mathbf{x}_t)}). \tag{13}$$

In equation (12), ingrowth for pine is obtained from the Pukkala et al. (2013) model, but ingrowth for birch is obtained from the Pukkala et al. (2011) growth model. In the Pukkala et al. (2013) specification birch ingrowth is even more abundant (unrealistically so) than in the Pukkala et al. (2011) specification (Parkatti & Tahvonen, 2020), which is why the latter is used in this thesis to substitute for birch ingrowth in the Pukkala et al. (2013) model. Equation (13) is the Pukkala et al. (2021) specification. The basal area ($m^2 \cdot ha^{-1}$) of species j is given by $\beta_j(\mathbf{x}_t)$, hence $\beta_{\text{birch}}(\mathbf{x}_t)$ represents the basal area of birch and $\beta_{\text{pine}}(\mathbf{x}_t)$ represents the basal area of pine. Silver birch and downy birch are not separated in the ingrowth models.

Ingrowth is at its maximum with low stand basal areas, but ingrowth with higher stand densities is where the ecological models differ the most (Figure 1c): in the Pukkala et al. (2011) model, the ingrowth of birch initially improves and then declines with increasing stand density, whereas in the Pukkala et al. (2021) model ingrowth is a decreasing convex function. The Pukkala et al. (2013) model predicts especially low ingrowth for the shade-intolerant pine – particularly with high stand densities – while the Pukkala et al. (2021) model gives significantly higher values for pine ingrowth. The ingrowth of birch is more plentiful; especially for higher stand basal areas in the Pukkala et al. (2011) model and low stand basal areas in the Pukkala et al. (2021) model. Pine ingrowth only exceeds that of birch in single-species stands in the Pukkala et al. (2021) model when basal area is at least 2 $m^2 \cdot ha^{-1}$. In the Pukkala et al. (2011, 2013) model, both birch and pine have higher ingrowth in single-species stands, whereas in the Pukkala et al. (2021) model, birch ingrowth is improved by the presence of pine. The effect of temperature sum on natural regeneration is incorporated in the Pukkala et al. (2021) model: ingrowth improves toward the south.

2.3 Computational methods

The optimal rotation length *T* and the binary harvest timing variables $(\delta_t : Z \in \{0,1\}, t \in [t_0, T])$ are integers, while the harvest intensities h_{jst} $(j = 1,...,l; s = 1,...,n; t = t_0, t_0 + 1,...)$ are continuous variables. Hence, the aim is to solve a nonlinear dynamic discrete-time mixed-integer optimization problem (1)-(5).

The optimization problem is solved as a tri-level problem: rotation length *T* is the upper-level problem, timing of thinnings is the middle-level problem and thinning intensity is the lowest-level problem. The upper-level problem is solved by varying the rotation length and choosing the bare land value maximizing rotation as the optimal one. Given *T*, the middle-level problem is solved by applying genetic and hill-climbing algorithms, while the lowest-level problem is solved by applying gradient-based algorithms with the Ampl/Knitro optimization software (version 12.2).

The transition path towards the steady state is solved simultaneously with the steady state. If the bare land value is maximized with some $T \in [40,180)$, the optimal rotation is considered finite and the optimal management regime is RF. On the other hand, the optimal rotation is considered infinite and the optimal regime is CCF, if increasing *T* up to 180 years increases the bare land value. In the infinite horizon solutions, it is assumed that the steady-state harvesting interval and stand structure are reached within a transition period consisting of seven harvests (with optimized intervals) and a 500-year time horizon. This horizon is long enough for the stand structure, harvest quantities and harvest intervals to start repeating as same, that is, to represent an optimal steady state. This implies that further lengthening the time horizon will not change the transition path towards the steady state. In the lowest-level problem, four random initial points are used for harvest timing vectors, due to potential nonconvexities.

3 Results

3.1 Optimal solutions

3.1.1 Pine

Table 1 shows optimal solutions for a pure Scots pine stand with $\mathbf{x}_{12t_0}$ = 2000 and 1100 d.d. The optimal rotation with the Pukkala et al. (2011, 2013) model and a 1% interest rate is 105 years (Figure 2a). The rotation includes three thinnings in which trees with a diameter larger than 22.5 cm are harvested. The bare land value equals €16770·ha^{-1}. Over the rotation, mean annual timber yield is 5.6 m^3·ha^{-1}, of which 87% is valuable sawlog, yielding mean annual revenues of €250.9·ha^{-1}. On average, only 2 new trees per hectare regenerate every year. When the interest rate equals 3%, the optimal regime shifts to CCF (Figure 2b). The optimal steady-state harvest interval is 20 years, and the harvests target trees with diameters of 17.5–32.5 cm. The bare land value equals €2377·ha^{-1}. By keeping the post-harvest basal area very low (1.5 m^2·ha^{-1}), the solution generates more ingrowth (on average 13 trees per year over the steady-state cycle). Nonetheless, the ingrowth of pine in this ecological model is very weak, which is why the mean annual yield in the steady state remains as low as 4.0 m^3·ha^{-1} (with a 82% sawlog ratio), implying mean annual net revenues of €145.8·ha^{-1}.

When the Pukkala et al. (2021) model is used, the optimal solution yields CCF with a 20-year steady-state harvest interval (Figures 2a, 2b). Steady-state harvests target trees with diameters of 22.5–37.5 cm when r = 1% and 17.5–32.5 cm when r = 3%. In this ecological model, pine ingrowth is stronger; on average 26 new trees with r = 1% and 33 trees with r = 3% regenerate annually in the steady state (Table 1). The solutions show that a higher interest rate leads to heavier harvests, which shows as lower stand density and intensified ingrowth. In both solutions, the stronger ingrowth together with the faster diameter increment of pine is reflected in higher timber yields (and a higher sawlog ratio for r = 1%), compared to the solutions computed with the Pukkala et al. (2011, 2013) model. With a 1% interest rate, 92% of the average annual yield of 5.8 m^3·ha^{-1} over the steady-state cycle is saw wood, whereas with a 3% interest rate the values are 76% and 6.3 m^3·ha^{-1}. These contribute to higher mean annual revenues in the steady state (€263.5·ha^{-1} for r = 1% and €250.7·ha^{-1} for r = 3%), and ultimately, higher bare land values: €20506·ha^{-1} for r = 1% and €3012·ha^{-1} for r = 3%. The better pine growth is also reflected in the post-harvest basal areas, 8.1 m^2·ha^{-1} for r = 1% and 4.9 m^2·ha^{-1} for r = 3%.

Table 1. Optimal solutions for a pure pine stand.

Interest rate (%)	Ecological model	Rotation length / steady state harvest interval (years)	Bare land value (€·ha^{-1})	Mean annual yield (m^3·ha^{-1})	Mean sawlog ratio of harvested volume (%)	Basal area before / after steady state harvests (m^2·ha^{-1})	Mean annual ingrowth (trees·ha^{-1})	Mean stand volume (m^3·ha^{-1})	Mean annual revenues (€·ha^{-1})
1 %	P13	105 / -	16770	5.6	87	-	2.0	126.4	250.9
	P21	∞ / 20	20505	5.8	92	18.4 / 8.1	26.0	99.6	263.5
3 %	P13	∞ / 20	2377	4.0	82	8.2 / 1.5	12.5	35.4	145.8
	P21	∞ / 20	3011	6.3	76	16.3 / 4.9	33.1	74.1	250.7

Note: 1100 d.d., $\mathbf{x}_{12t_0}$ = 2000, w = 1489/1401. P13 refers to Pukkala et al. (2011, 2013) and P21 to Pukkala et al. (2021). Mean values are measured over the rotation or the steady-state cycle.

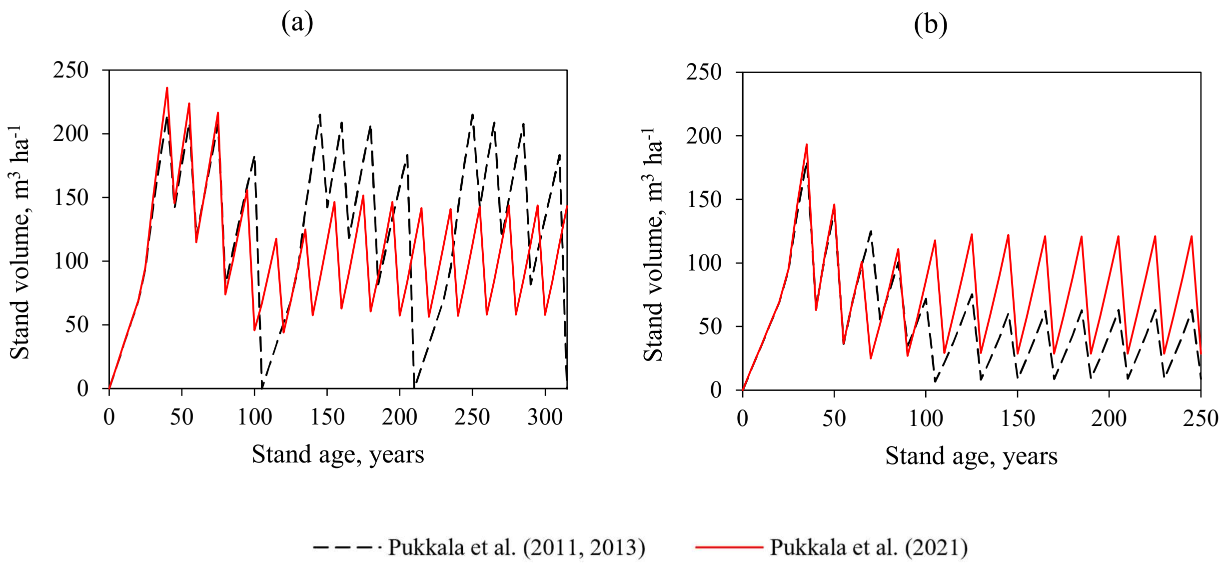

Figure 2a-b. Optimal stand volume developments of a pure pine stand with an interest rate (a) r = 1% and (b) r = 3%.
Note: 1100 d.d., $\mathbf{x}_{12t_0}$ = 2000, w = 1489/1401.

Increasing the temperature sum generates stronger forest growth; in the Pukkala et al. (2011, 2013) model only through diameter increment, but with the Pukkala et al. (2021) model also through ingrowth. When temperature sum is 1300 d.d., the bare land values computed with the Pukkala et al. (2011, 2013) model equal €20253·ha^{-1} for r = 1% and €3127·ha^{-1} for r = 3%. The solutions look very similar to those computed with 1100 d.d. – with a 1% interest rate, harvests simply yield more timber with a higher ratio of sawlog, and with a 3% interest rate, the steady-state harvests become more frequent (every 15 years), albeit lighter, resulting in a higher mean annual timber yield. The latter also happens in the CCF solutions computed with the Pukkala et al. (2021) model: consequently, bare land value increases to €26257·ha^{-1} for r = 1% and €4172·ha^{-1} for r = 3%.

3.1.2 Birch

Table 2 presents optimal solutions for a pure birch stand with $\mathbf{x}_{22t_0}$ = 1600 and 1100 d.d. A pure birch stand yields continuous cover forestry with a 20-year harvesting interval (Figure 3a) when the Pukkala et al. (2011, 2013) model is applied with a 1% interest rate. Trees with a diameter of 22.5–37.5 cm are harvested at the steady state. The bare land value equals €10555·ha^{-1}. Mean annual yield in the steady state is 5.1m^3·ha^{-1}, with an 82% share of valuable saw wood, and the mean annual revenues equal €173.8·ha^{-1}. Average annual ingrowth is 49 trees per hectare over the steady-state cycle. With a 3% interest rate, bare land value is €516·ha^{-1}. The steady-state harvesting interval is shortened to 15 years (Figure 3b), with harvests targeting trees with diameters of 22.5–32.5 cm. This boosts the average annual ingrowth in the steady state to 51 trees per year and allows for a slightly higher mean stand volume and annual yield (5.5m^3·ha^{-1}, of which 81% sawlog). Steady-state annual revenues equal €170.0·ha^{-1} on average. The post-harvest basal areas are 13.6m^2·ha^{-1} and 14.6m^2·ha^{-1} for r = 1% and r = 3%, respectively.

Applying the Pukkala et al. (2021) model, the outcome is rotation forestry without artificial regeneration (in computational terms, this implies to CCF with near-clearcuts). The solutions include two different transition rotations, after which it is assumed that the third steady-state rotation is repeated ad infinitum. With a 1% interest rate, the optimal steady-state rotation is 110 years with three thinnings and a near-clearcut (Figure 3a). The first and second thinnings remove all trees with a diameter larger than 22.5 cm, and the third thinning removes those larger than 27.5 cm. With a 3% interest rate, the steady-state rotation shortens to 95 years with four thinnings (targeting trees with a diameter larger than 22.5 cm) and a near-clearcut (Figure 3b). In the near-clearcuts at the end of each rotation, practically all trees with a positive roadside price (that is, all trees except for the smallest size class) are removed, in order to create a new tree generation through natural regeneration. The reason for such a solution is that in the Pukkala et al. (2021) model, the only way to generate birch ingrowth is to bring the basal area close to zero – this way, ingrowth becomes abundant. The Pukkala et al. (2021) solutions result in higher bare land values (€14636·ha^{-1} for r = 1% and €1419·ha^{-1} for r = 3%), compared to the solutions computed with the Pukkala et al. (2011, 2013) model. This can be credited to the faster diameter increment of birch in the Pukkala et al. (2021) model, combined with the ingrowth boost created via near-clearcuts. With r = 1%, periodic near-clearcuts generate an average of 21 ingrowth trees annually per hectare over the steady-state rotation, whereas with r = 3% the number is 23 trees (Table 2). (Due to weaker ingrowth with high basal areas, the solutions still yield lower total ingrowth than those computed with the Pukkala et al. (2011, 2013) model). Consequently, the Pukkala et al. (2021) solutions generate higher annual timber yields over the steady-state rotation: on average 6.2 m^3·ha^{-1} for r = 1% and 6.0 m^3·ha^{-1} for r = 3%. For r = 1%, the sawlog ratio of this harvested volume is 84%, whereas for r = 3% the value is 78% (due to the more frequent harvests). Average annual net revenues over the steady-state rotation equal €228.6·ha^{-1} for r = 1% and €200.2·ha^{-1} for r = 3%.

In the Pukkala et al. (2011, 2013) model, higher temperature sum implies faster diameter increment of birch, whereas with the Pukkala et al. (2021) model it also has a positive effect on natural regeneration. In the CCF solutions obtained with the Pukkala et al. (2011, 2013) model, increasing the temperature sum to 1300 d.d. translates into a shorter harvesting interval (15 years) and higher annual yields on average. Consequently, bare land value increases to €12690·ha^{-1} with r = 1% and to €954·ha^{-1} with r = 3%. With the Pukkala et al. (2021) model, faster forest growth shortens the harvesting cycles both during the transition period and the steady state: optimal steady-state rotation shortens to 95 years with a 1% interest rate and to 85 years with a 3% interest rate. Moreover, thinnings become more frequent (albeit less intense), resulting in higher mean annual yields. Bare land value goes up to €20395·ha^{-1} for r = 1% and to €2470·ha^{-1} for r = 3%.

Table 2. Optimal solutions for a pure birch stand.

Interest rate (%)	Ecological model	Rotation length / steady state harvest interval (years)	Bare land value (€·ha^{-1})	Mean annual yield (m^3·ha^{-1})	Mean sawlog ratio of harvested volume (%)	Basal area before / after near-clearcut or steady state harvests (m^2·ha^{-1})	Mean annual ingrowth (trees·ha^{-1})	Mean stand volume (m^3·ha^{-1})	Mean annual revenues (€·ha^{-1})
1 %	P13	∞ / 20	10555	5.1	82	22.9 / 13.6	49.4	118.6	173.8
	P21	110* / -	14636	6.2	84	18.4 / 0.02	21.3	141.3	228.6
3 %	P13	∞ / 15	515	5.5	81	21.1 / 14.6	51.2	111.7	170.0
	P21	95* / -	1419	6.0	78	16.0 / 0.05	23.3	90.3	200.2

Note: 1100 d.d., $\mathbf{x}_{22t_0}$ = 1600, w = 1489/1401. P13 refers to Pukkala et al. (2011, 2013) and P21 to Pukkala et al. (2021). Mean values are measured over the steady-state cycle or steady-state rotation. *RF without artificial regeneration; values are shown for the steady-state rotation.[1]

[1] The steady-state rotation is a well-founded point of comparison for the RF without artificial regeneration -solutions, despite the fact that the majority of the net present value of forestry income consists of the transition harvests. The key figures presented for the steady-state rotation are, in practice, the same also for the second transition rotation.

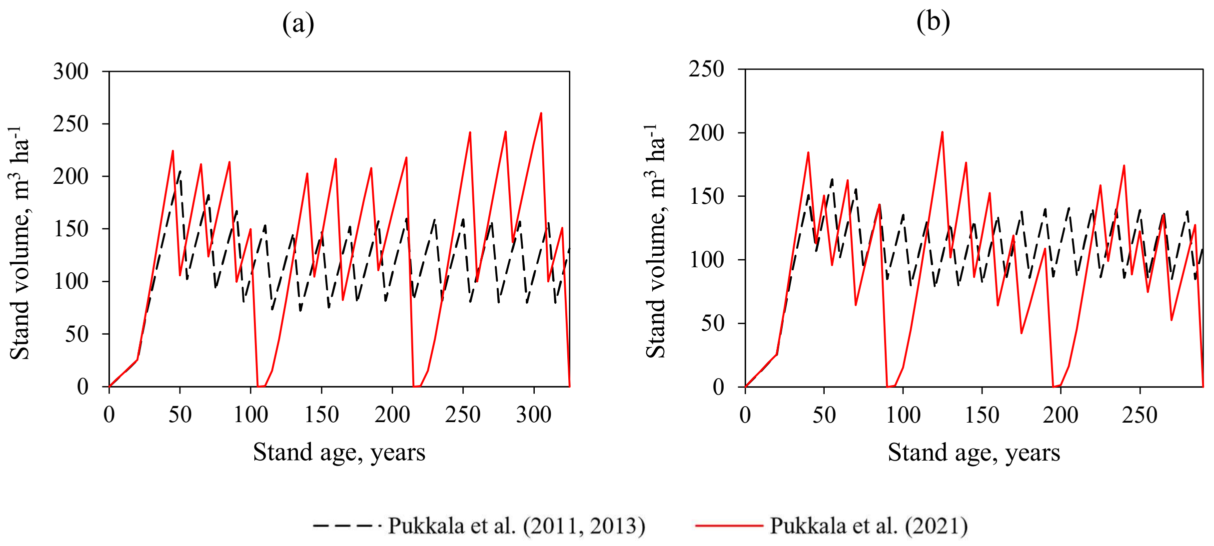

Figure 3a-b. Optimal stand volume developments of a pure birch stand with an interest rate (a) r = 1% and (b) r = 3%.
Note: 1100 d.d., $\mathbf{x}_{22t_0}$ = 1600, w = 1489/1401.

3.1.3 Pine and birch mixture

Optimal solutions for mixed pine–birch stands with $\mathbf{x}_{j2t_0}$ = [2000, 200] and 1100 d.d. are presented in Table 3. The optimal rotation length for a mixed stand with the Pukkala et al. (2011, 2013) model is 120 years with four thinnings (Figure 4a), when r = 1%. The bare land value equals €16696·ha^{-1}. Average annual timber yield over the rotation is 6.9 m^3·ha^{-1}, with an 86% share of saw wood, yielding average annual net revenues of €246.7·ha^{-1}. All throughout the rotation, the stand is dominated by pine, with a 79% proportion of the harvested volume at clearcut. Yet, the total average annual ingrowth of 19 trees over the rotation derives almost entirely from birch. With a 3% interest rate, the solution shifts to continuous cover forestry with a 20-year steady-state harvest interval (Figure 3c). The stand almost turns into a pure birch stand, with 94% of the steady-state harvested volume being birch. Birch trees with a diameter larger than 17.5 cm and pine trees with a diameter larger than 22.5 cm are harvested in steady-state thinnings. The bare land value equals €2373·ha^{-1}. Mean annual timber yield in the steady state is 6.0 m^3·ha^{-1}, but only 47% of the harvested volume is saw wood, because many birch trees are harvested just before they are about to give timber. It is profitable to harvest birch primarily for pulpwood, since the lower sawlog value of birch undermines the value increment from postponing harvests. Further, bringing the basal area down via more intensive harvests helps create space for more abundant birch ingrowth. Mean annual revenues over the steady-state cycle equal €162.8·ha^{-1}. Birch generates almost all of the 65 average annual ingrowth trees per hectare in the steady state.

Applying a 1% interest rate and the Pukkala et al. (2021) model leads to RF without artificial regeneration. The steady-state rotation after two transition cycles is 110 years (Figure 4b). The thinnings target birch trees with a diameter larger than 22.5 cm and pine trees with a diameter larger than 27.5 cm. At the end of the rotation, a near-clearcut is performed: with pine, the harvests target size classes 17.5–37.5 cm, while all birch trees apart from the smallest size class are harvested (Figure 5a). As a result, a total of 97% of stand volume is removed. By creating space for the existing young size classes and abundant birch ingrowth, a new tree cohort is generated without artificial regeneration. The bare land value (€24056·ha^{-1}) exceeds that given by the Pukkala et al. (2011, 2013) solution. This happens by virtue of the faster diameter increment in the Pukkala et al. (2021) model, combined with the stronger pine ingrowth and the usage of near-clearcuts to capitalize on the strong birch ingrowth at low basal areas. Table 3 shows that on average, 48 new trees (of which 60% birch and 40% pine) per hectare regenerate every year over the steady-state rotation. That is more than double compared to the solution obtained with the Pukkala et al. (2011, 2013) model. Consequently, the mean annual timber yield (8.2 m^3·ha^{-1}) over the steady-state rotation is higher in this solution. Compared to the Pukkala et al. (2011, 2013) solution, the share of saw wood (81%) is lower due to the more frequent thinnings, and the proportion of less valuable birch at the near-clearcut (68%) is more than triple. Yet, the better forest growth enables higher mean annual net revenues (€317.9·ha^{-1}) over the steady-state rotation.

With a 3% interest rate, the Pukkala et al. (2021) solution switches to continuous cover forestry (Figure 4d). Birch is still the dominant species in the stand. Steady-state harvests target pine and birch trees with a diameter larger than 22.5 cm (Figure 5c). Average annual ingrowth over the steady-state cycle equals 39 trees (of which 49% birch and 51% pine), which is noticeably less than with the Pukkala et al. (2011, 2013) model; without near-clearcuts some of the ingrowth potential of birch in the Pukkala et al. (2021) model is lost. However, due to the faster diameter increment, steady-state thinning interval is 15 years, and the mean annual yield (7.4 m^3·ha^{-1}) exceeds that given by the Pukkala et al. (2011, 2013) model. The share of valuable saw wood of steady-state harvests is 85%, close to double compared to the solution obtained with the Pukkala et al. (2011, 2013) model. Also, by virtue of the significantly stronger pine ingrowth, one third of the steady-state harvested volume is economically more valuable pine. As a result, this solution yields higher mean annual steady-state revenues (€280.5·ha^{-1}) and bare land value (€3364·ha^{-1}), compared to the Pukkala et al. (2011, 2013) solution.

In the Pukkala et al. (2011, 2013) solution for r = 1%, increasing the temperature sum to 1300 d.d. causes the optimal rotation length to shorten to 115 years. Due to the stronger forest growth, the share of pine trees in the stand is relatively higher, more timber with a higher sawlog ratio can be harvested per thinning, and bare land value rises to €20163·ha^{-1}. With r = 3%, the same change in the temperature sum intensifies the transition harvests, and the steady-state harvests yield more timber from each size class, as well as a higher sawlog ratio, leading to a bare land value of €3115·ha^{-1}. In the Pukkala et al. (2021) solution for a 1% interest rate, temperature sum of 1300 d.d. shortens the rotation lengths and thinning intervals both during the transition period and the steady state. Mean annual timber yield increases and bare land value rises to €31364·ha^{-1}. With r = 3%, 1300 d.d. makes the transition harvests more frequent and shortens the steady-state harvest interval to 10 years, implying less timber harvested per thinning but a higher annual yield on average. Bare land value equals €4785·ha^{-1}.

Table 3. Optimal solutions for a mixed pine–birch stand.

Interest rate (%)	Ecological model	Rotation length / steady state harvest interval (years)	Bare land value (€·ha^{-1})	Mean annual yield (m^3·ha^{-1})	Mean sawlog ratio of harvested volume (%)	Basal area before / after near-clearcut or steady state harvests (m^2·ha^{-1})	Mean annual ingrowth, birch / pine / total (trees·ha^{-1})	Mean stand volume (m^3·ha^{-1})	Average species-specific volume proportion, pine / birch (%)	Mean annual revenues (€·ha^{-1})
1 %	P13	120 / -	16696	6.9	86	-	17.1 / 1.8 / 18.9	131.6	79 / 21	246.7
	P21	110* / -	24056	8.2	81	21.7 / 1.1	29.0 / 19.4 / 48.4	162.2	32 / 68	317.9
3 %	P13	∞ / 20	2372	6.0	47	22.3 / 10.6	63.8 / 1.3 / 65.1	95.5	6 / 94	162.8
	P21	∞ / 15	3363	7.4	85	21. 5 / 12.7	19.4 / 19.9 / 39.3	119.0	34 / 66	280.5

Note: 1100 d.d., $\mathbf{x}_{j2t_0}$ = [2000, 200], w = 1489/1401. P13 refers to Pukkala et al. (2011, 2013) and P21 to Pukkala et al. (2021). Mean values are measured over the rotation or the steady-state cycle. Species-specific volume proportions refer to harvested volume from (near-) clearcuts or steady-state thinnings.
*RF without artificial regeneration; values are shown for the steady-state rotation.[2]

[2] The steady-state rotation is a well-founded point of comparison for the RF without artificial regeneration -solutions, despite the fact that the majority of the net present value of forestry income consists of the transition harvests. The key figures presented for the steady-state rotation are, in practice, the same also for the second transition rotation.

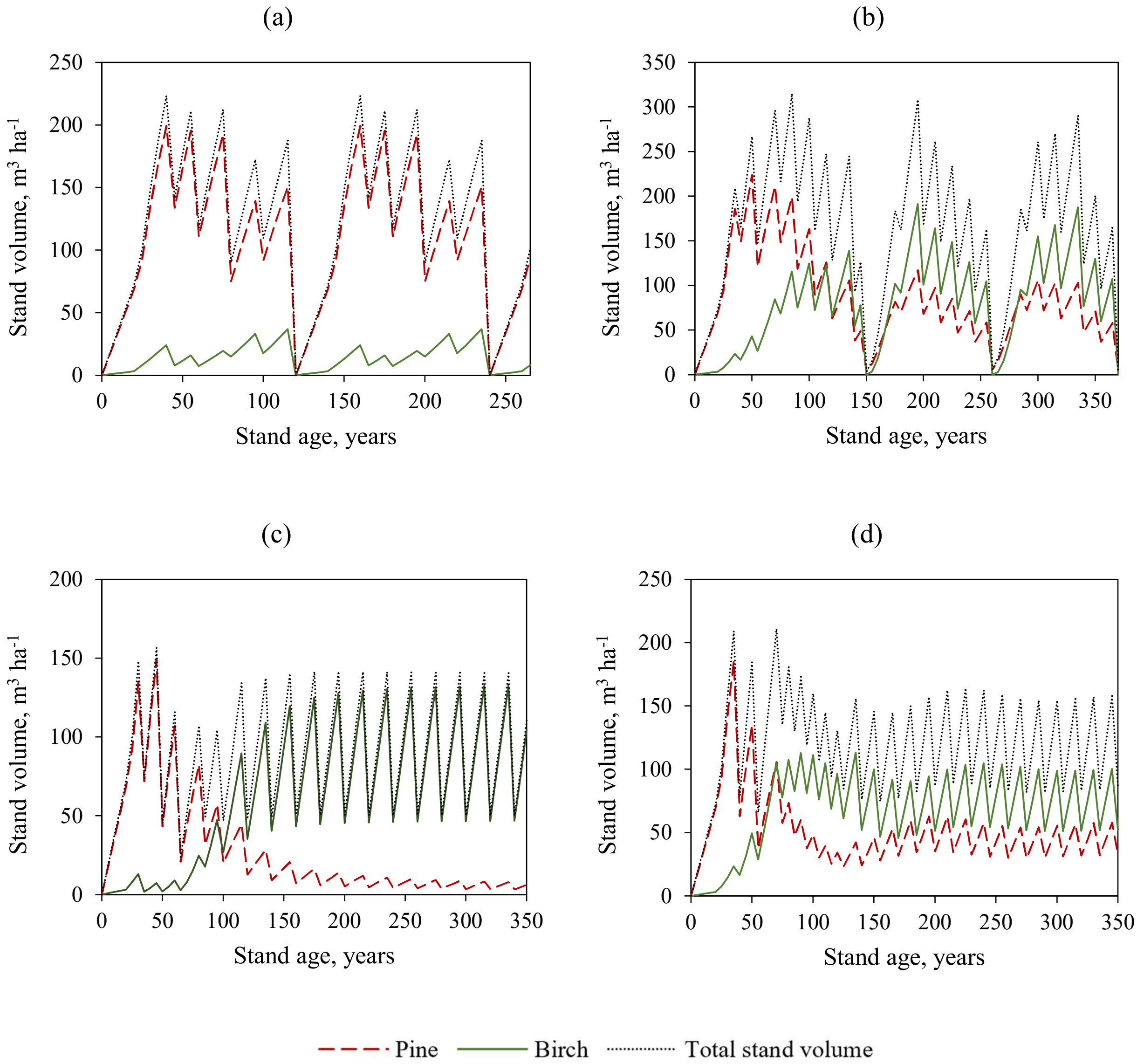

Figure 4a-d. Optimal stand volume developments of a mixed pine–birch stand with (a, c) the Pukkala et al. (2011, 2013) model and (b, d) the Pukkala et al. (2021) model.
Note: interest rate r = 1% in (a) and (b) and interest rate r = 3% in (c) and (d). 1100 d.d., $\mathbf{x}_{j2t_0}$ = [2000, 200], w = 1489/1401.

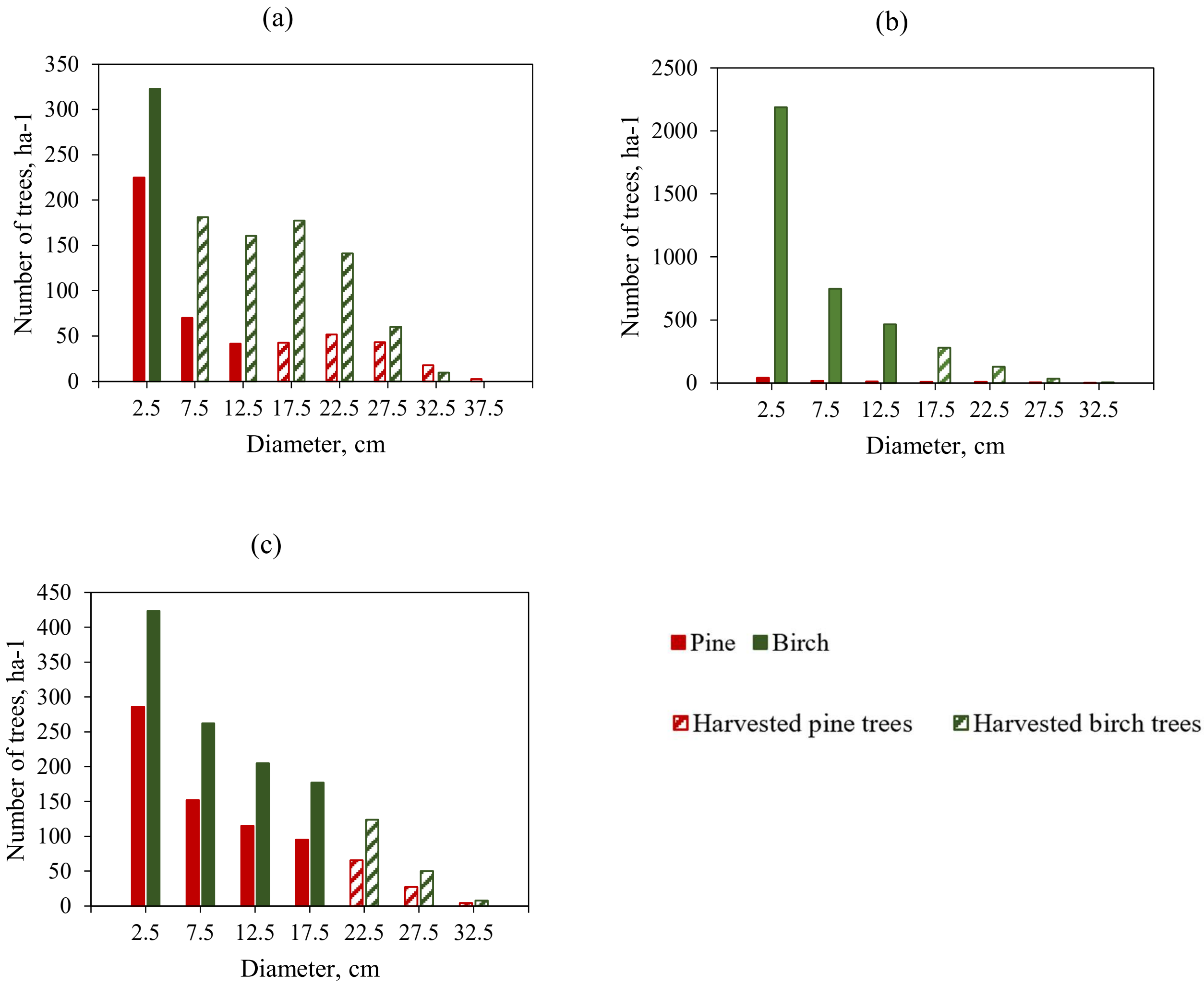

Figure 5a-c. Optimal steady-state stand structure of a mixed pine–birch stand with (a, c) the Pukkala et al. (2021) model and (b) the Pukkala et al. (2011, 2013) model.
Note: interest rate r = 1% in (a) and interest rate r = 3% in (b) and (c). 1100 d.d., $\mathbf{x}_{j2t_0}$ = [2000, 200], w = 1489/1401. (a) illustrates the near-clearcut at the end of the steady-state rotation.

3.2 Optimal choice of the management regime

All in all, optimal solutions were computed for five different initial states: a pure pine stand with 2000 pine trees ($\mathbf{x}_{12t_0}$ = 2000), a pure birch stand with 1600 birch trees ($\mathbf{x}_{22t_0}$ = 1600) and a mixed stand with 2000 pine trees and either 0 birch trees ($\mathbf{x}_{j2t_0}$ = [2000, 0]), 200 birch trees ($\mathbf{x}_{j2t_0}$ = [2000, 200]) or 400 birch trees ($\mathbf{x}_{j2t_0}$ = [2000, 400]). Optimal management regimes and bare land values for all cases with a positive regeneration cost are presented in Table 4.

With the Pukkala et al. (2011, 2013) model and r = 1%, the optimal management regime for a pure pine stand is rotation forestry. With a 3% interest rate, investing into artificial regeneration can no longer provide a high enough level of return and compete with natural regeneration: maintaining a more stable flow of forest income via continuous cover management becomes more profitable. However, similarly to previous studies (Parkatti et al., 2019; Parkatti & Tahvonen, 2020), the suitability of CCF for pine seems questionable due to its weak ingrowth and the consequential very low stand density (see Table 1). With r = 3%, the regime switches back to RF when artificial regeneration is free (with 1100 d.d., optimal rotation is 90 years and the bare land value equals €3818·ha^{-1}, whereas with 1300 d.d., the values are 75 years and €4557·ha^{-1}).

With the Pukkala et al. (2021) model, the optimal management regime for pine is CCF, regardless of the interest rate. The post-harvest basal areas of these solutions (Table 1 for 1100 d.d.) are higher than with the Pukkala et al. (2011, 2013) model, but do still not satisfy the legal lower-bound restriction of 9 m^2·ha^{-1} set for CCF harvests in Central Finland or 10 m^2·ha^{-1} for Southern Finland (Forest Decree 1308/2013; FINLEX 2013). A violation of this restriction leads to a regeneration obligation. Still, the suitability of CCF for pine seems somewhat less questionable in light of the Pukkala et al. (2021) model. This can be credited to the faster diameter increment and stronger ingrowth of pine. RF only becomes optimal with r = 1% and 1100 d.d. when artificial regeneration is free: optimal rotation length is 95 years and the bare land value equals €22517·ha^{-1}.

Birch is characterized by stronger ingrowth and somewhat lower mortality compared to pine. That is why a pure birch stand always yields CCF, when the Pukkala et al. (2011, 2013) model is used. However, the CCF steady states include relatively high post-harvest basal areas (see Table 2). It is unclear whether birch, as a light-demanding pioneer species (Hynynen et al., 2010), could really regenerate with such high stand densities. Compared to the Pukkala et al. (2011, 2013) model, the Pukkala et al. (2021) model predicts faster diameter increment (especially for large birch trees) and better birch ingrowth but only for low stand basal areas. Hence, the optimal management regime with the Pukkala et al. (2021) model is RF without artificial regeneration. Artificial regeneration is only utilized when it is free and temperature sum equals 1100 d.d., but even then, optimal rotations are as long as 180 years for r = 1% and 175 years for r = 3%. Otherwise, artificial regeneration is not utilized, because it is more profitable to take advantage of the existing smallest size class (left unharvested at near-clearcut) and natural regeneration in generating a new tree cohort. This way, regeneration is faster (see Figures 3a-b). In practice, a management strategy involving near-clearcuts would seem to be more in line with the fact that as a pioneer species, birch demands a lot of light.

For mixed pine–birch stands, the optimization gives pine-dominated rotation forestry when interest rate equals 1% and the Pukkala et al. (2011, 2013) model is applied. In this ecological model, the ingrowth of pine is particularly weak, whereas birch regenerates well even with high stand densities. With a 3% interest rate, the cost of waiting for the slow value increment of the valuable pine tree stock increases. That is why it becomes optimal to switch to CCF and take advantage of the strong birch ingrowth by letting it dominate the stand almost fully. However, the post-harvest basal areas given by the CCF solutions (for instance, 10.6 $m^2 \cdot ha^{-1}$ with 1100 d.d.; Table 3) seem quite high, considering the stand consists almost purely of birch. The same question is provoked as with respect to pure birch stands: given that birch is a light-demanding pioneer species (Hynynen et al., 2010), could birch really regenerate with such high basal areas, such that the steady state could be maintained?

On the other hand, with the Pukkala et al. (2021) model and r = 1%, the optimal way to manage mixed pine–birch stands is RF without artificial regeneration. The stands are dominated by birch (see Table 3), despite its lower sawlog value and its disruptive effect on pine ingrowth, because it regenerates better than pine. In the Pukkala et al. (2021) model, birch ingrowth reacts to basal area very strongly, which is why near-clearcuts are conducted to generate vigorous birch ingrowth and to make space for the existing small size classes. Artificial regeneration is not used even when it is free – except for when r = 1% and temperature sum equals 1100 d.d. With a 3% interest rate, the optimal regime shifts to CCF. The stand is dominated by birch for the same reason as with r = 1%. The more equal split between pine and birch in the stand (see Table 3) makes this solution more credible, compared to the CCF solution given by the Pukkala et al. (2011, 2013) model.

Table 4. Maximized bare land values ($€ \cdot ha^{-1}$) and optimal management regimes for pure pine stands, pure birch stands, and mixed pine–birch stands.

TS	**1100**				**1300**			
r	*1 %*		*3 %*		*1 %*		*3 %*	
x_{t_0}	P13	P21	P13	P21	P13	P21	P13	P21
x_{22t_0} = 1600	10555	14636* (110)	516	1419* (95)	12690	20395* (95)	954	2470* (85)
x_{12t_0} = 2000	16770 (105)	20506	2377	3012	20253 (105)	26257	3127	4172
x_{j2t_0} = [2000, 0]	16766 (105)	24142* (115)	2382	3356	20248 (105)	31664* (90)	3133	4791
x_{j2t_0} = [2000, 200]	16696 (120)	24056* (110)	2373	3364	20163 (115)	31364* (95)	3115	4785
x_{j2t_0} = [2000, 400]	16676 (115)	24026* (100)	2351	3374	20195 (110)	31361* (90)	3103	4792

Note: w = 1489/1401. Initial states are given by $\mathbf{x}_{jst_0}$. P13 refers to Pukkala et al. (2011, 2013) model and P21 to Pukkala et al. (2021) model. Rotation length (in years) is shown in parenthesis. In coloured (non-coloured) cells, CCF (RF) is optimal. * = RF without artificial regeneration; rotation length is given for the steady-state rotation.

3.3 Optimizing the species composition in a pine–birch mixture

As a pioneer species, birch often naturally regenerates in pine stands (Hynynen et al., 2010). In such a situation, birch trees can either be removed during seedling stand management and/or thinnings, or the birch trees can be left to the stand, for it to evolve into a pine–birch mixture. The optimal species composition is not only affected by the relative roadside prices of each species, but also the species-specific growth patterns and most opportune growth periods. In the case of a pine–birch mixture, the degree of potential economic benefit from mixing these two shade-intolerant species (Hynynen et al., 2010) comes down to whether the abundant birch ingrowth can be taken advantage of, without disrupting the pine growth too much. Moreover, mixing birch with pine can improve the stem quality of birch, and in *MT* forest sites the consequential increase in seedling stand density can reduce the branch sizes of pine (Hynynen et al., 2010; Äijälä et al., 2019). All solutions involving pine trees ($\mathbf{x}_{22t_0} = 2000$, $\mathbf{x}_{j2t_0} = [2000, 0]$, $\mathbf{x}_{j2t_0} = [2000, 200]$ and $\mathbf{x}_{j2t_0} = [2000, 400]$) were analysed to examine the economically optimal species composition in a pine–birch mixture.

Applying the Pukkala et al. (2011, 2013) model and a 1% interest rate, it is economically optimal to maintain a pure pine stand and remove all birch trees during seedling stand management. This outcome derives from the disruptive effect of birch on pine ingrowth and diameter increment. Adding more birch trees into the initial state leads to birch taking up larger proportions of the stand density after each thinning, hence slowing down the ingrowth and diminishing the stand volume of pine. (With 1100 d.d., the proportion of birch of total stand volume before clearcut is 0% for $\mathbf{x}_{j2t_0}$ = [2000, 0], 20% for $\mathbf{x}_{j2t_0}$ = [2000, 200] and 22% for $\mathbf{x}_{j2t_0}$ = [2000, 400]). Adding more birch does improve the total ingrowth and average yield, but the positive impacts are overridden by a decrease of the saw wood ratio and a partial replacement of pine with lower-value birch in harvested volume. Hence, Table 4 shows that more birch trees in the initial state generally implies a lower bare land value. While the two cases with an identical initial state ($\mathbf{x}_{22t_0}$ = 2000 and $\mathbf{x}_{j2t_0}$ = [2000, 0]) yield an almost identical solution, bare land value is slightly lower when the regeneration of birch is not restricted. This is due to the additional costs of having to harvest a small number of birch trees at clearcut.

Applying the Pukkala et al. (2011, 2013) model and a 3% interest rate, the optimal regime shifts to CCF. The steady states are identical for the cases in which birch can regenerate: birch takes over the stand, such that 94% of the stand volume before steady-state harvests is birch. The bare land value for $\mathbf{x}_{j2t_0}$ = [2000, 0] just exceeds that for $\mathbf{x}_{22t_0}$ = 2000: in a birch-dominated stand, the better ingrowth enables a higher annual yield, although the profitability is impaired by the lower sawlog ratio of steady-state harvests, and the lower value of birch sawlog compared to pine. However, the higher the number of birch trees in the initial state increases, the more frequent the transition harvests become, allowing birch to take up more space from pine earlier on and to constitute a bigger portion of harvested volume during the transition. This leads to a decrease in bare land value, as shown in Table 4. Therefore, it is economically beneficial to let birch dominate the stand almost entirely in the steady state, but only if the presence of birch is minimized at the early stages of stand development – otherwise a pure pine stand yields a higher bare land value. It is to be noted that the credibility of these solutions was put into question in the previous chapter, and the differences between their bare land values are minor.

A more balanced conclusion is obtained with the Pukkala et al. (2021) model: with r = 1%, it is optimal to let birch dominate the stand all throughout the steady-state rotation and increase its proportion of the total stand volume up to 63% prior to near-clearcut. The pure pine stand is managed through CCF, but allowing for the regeneration of birch switches the optimal regime to RF without artificial regeneration. The mixed stands are dominated by birch: the birch ratios of total stand volume in the steady-state rotation – before the first thinning and before near-clearcut (respectively) – are 54% and 63% for $\mathbf{x}_{j2t_0}$ = [2000, 0], 51% and 65% for $\mathbf{x}_{j2t_0}$ = [2000, 200] and 55% and 65% for $\mathbf{x}_{j2t_0}$ = [2000, 400] with 1100 d.d. The pure pine stand yields the lowest bare land value, because the weak ingrowth limits the average annual timber yield. Including birch in the mixture nearly doubles the mean annual ingrowth and increases the average annual yield but decreases the sawlog ratio of harvests. In the birch-dominated stands, however, the bare land value decreases as the number of birch trees in the initial state increases (see Table 4), since the stronger presence of birch degrades the pine income (through weakened ingrowth) during the transition period. In contrast to the Pukkala et al. (2011, 2013) model, the Pukkala et al. (2021) model allows for faster diameter increment, more abundant pine ingrowth and stronger birch ingrowth with low basal areas. That is why birch-dominated solutions for r = 1% only become optimal with the Pukkala et al. (2021) model.

With the Pukkala et al. (2021) model and a 3% interest rate, the optimal management regime shifts to CCF but the same conclusion holds: it is profitable to let birch dominate the stand to the extent that 63% of the stand volume before steady-state harvests is birch. This allows for somewhat stronger average ingrowth in mixed-species solutions, which in turn shows as a shorter steady-state harvest interval (with 1100 d.d., 15 years, as opposed to 20 years with pure pine), a higher mean annual yield and a higher proportion of saw wood. These aspects result in higher bare land values for mixed stands, compared to a pure pine stand, even though the presence of birch implies a lower proportion of pine, which is of higher economic value. The more birch trees there are in the initial state, the higher the bare land value rises when temperature sum equals 1100 d.d. (see Table 4): with r = 3%, it is profitable to take advantage of the strong birch ingrowth already during the transition period, even when it disrupts the ingrowth of pine. Compared to the solutions computed with the Pukkala et al. (2011, 2013) model (with weak pine ingrowth and abundant birch ingrowth), the species-proportions with the Pukkala et al. (2021) model are more even, because pine ingrowth in this ecological model is stronger and birch ingrowth with higher stand basal areas more moderate.

4 Discussion

Previous optimization studies have concluded that continuous cover forestry is supported by high artificial regeneration costs and high interest rates (Parkatti et al., 2019; Tahvonen & Rämö, 2016). Species characteristics, especially natural regeneration, have also been shown to have an impact on the optimal regime choice (Parkatti et al., 2019; Parkatti & Tahvonen, 2020). The results of this thesis are in line with these remarks. This thesis also affirms the previously established result (Parkatti et al., 2019; Parkatti & Tahvonen, 2020; Tahvonen & Rämö, 2016) that thinnings from above are economically superior to thinnings from below; the harvesting of large trees makes space for smaller trees of which the future value increment is higher. In this thesis, thinnings from above remove 48–89% of stand volume in CCF steady-state thinnings and 31–68% of stand volume in RF thinnings. Similarly to previous studies (Tahvonen & Rämö, 2016), CCF generates less timber but higher shares of saw wood, albeit the latter point is only supported by the solutions computed with the Pukkala et al. (2021) model.

Previous optimization literature has not supported the continuous cover management of boreal pine stands due to the weak ingrowth of pine (Parkatti et al., 2019; Parkatti & Tahvonen, 2020). In this thesis, this conclusion holds when the Pukkala et al. (2011, 2013) model is used: CCF is only optimal with a 3% interest rate, but the weak ingrowth and very low stand density suggest the regime choice is questionable. However, in light of the solutions computed with the new Pukkala et al. (2021) model, the statement could be loosened: by virtue of better pine ingrowth in the Pukkala et al. (2021) model, the optimization produces more credible CCF solutions for pine stands in Central and Southern Finland.

The CCF solutions for pure birch stands, obtained with the Pukkala et al. (2011, 2013) model, may not be completely reliable. This is because the Pukkala et al. (2011) model (used in this thesis to describe birch ingrowth) gives excessive predictions. In reality, high stand densities impair the abundant birch ingrowth and can also make the stem form of birch slender (Hynynen et al., 2010). On the other hand, the results computed with the Pukkala et al. (2021) model suggest that the optimal way to manage birch stands is RF without artificial regeneration. This type of management strategy has only been presented theoretically in Tahvonen (2015) and would seem to be more in line with the early successional and light-demanding nature of birch (Hynynen et al., 2010). Near-clearcuts create favourable conditions for abundant birch ingrowth: a new tree generation develops from the unharvested young tree stock and naturally regenerated new trees, such that the investment into artificial regeneration can be avoided. The solutions naturally fulfil the Finnish Forest Decree (1308/2013; FINLEX 2013) regeneration obligation that determines minimum bounds for the number of young trees in the stand after harvesting. Given that the ecological growth models used in this thesis do not capture the fact that larger trees produce more seeds than small ones (Mukassabi et al., 2012; Rousi et al., 2011), the seed production in the remaining young tree stock after a near-clearcut is likely overestimated. Hence, the RF solutions without artificial regeneration describe a setup where natural regeneration also relies on seeds from nearby stands. In general, birch stands yield lower bare land values than pine stands due to the lower roadside price of birch sawlog.

According to previous studies, CCF is profitable in mixed-species stands, especially with high interest rates and high regeneration costs (Haight & Monserud, 1990; Parkatti et al. 2019; Parkatti & Tahvonen, 2020). This thesis affirms the conclusion also for pine–birch mixtures in Central and Southern Finland: with a 3% interest rate, CCF is the optimal regime with both ecological models. This thesis only computed solutions with Scots pine and silver birch. However, in practice, the birch tree stock could also contain downy birch, which grows slower than silver birch (Pukkala et al., 2021). This would likely decrease the profitability of CCF in birch-dominated mixed stands. With a 1% interest rate, rotation forestry becomes optimal, although with the Pukkala et al. (2021) model regeneration relies on the young, unharvested tree stock and seeds from nearby stands, rather than artificial regeneration. The RF solutions without artificial regeneration naturally fulfil the regeneration obligation set by the Finnish Forest Decree (1308/2013; FINLEX 2013).

Previously, the economically optimal species composition of a mixed pine–birch stand has been studied in Valsta (1986), where the optimal proportion of birch was found to be 20–40% early in the rotation, with a gradual decrease towards the end of the rotation. In this thesis, with the Pukkala et al. (2011, 2013) model and a 1% interest rate, it is optimal to maintain a pure pine stand due to the disruptive effect of birch on pine growth, whereas with a 3% interest rate the strongly regenerating birch dominates the steady state almost entirely. As discussed earlier, these solutions may not be completely reliable, due to excessive birch ingrowth. With the Pukkala et al. (2021) model, it becomes optimal to let birch constitute more than half of the stand volume all throughout the steady-state rotation or cycle and to increase the birch ratio to 63% of total stand volume prior to steady-state harvests (that is, prior to near-clearcuts when r = 1%). The outcomes differ from Valsta (1986) because their model did not include natural regeneration, seedling stand management nor optimization of the management regime. However, the economic loss from maintaining a 50% proportion of birch over the rotation was said to be minor in Valsta (1986). That would support the outcome of this thesis: despite the loss in income caused by the lower economic value of birch and its disruptive effect on pine growth, including birch in a pine stand is economically beneficial due to improvements in overall ingrowth. Hence, potential wood quality issues of pine on *MT* forest sites can be alleviated by increasing the stand density via natural birch regeneration, without economic losses. This conclusion, however, is strongly dependent on the ecological model used.

A major source of uncertainty in this thesis are the ecological growth models. Differences mainly derive from the data sets: the Pukkala et al. (2021) model relies on more recent data with a better geographic coverage, where the effects of recent climate change and nitrogen deposition affect forest growth. The most drastic differences between the two models concern natural regeneration (see Figure 1c). Of special note is the ingrowth of birch in the Pukkala et al. (2011) model (used in this thesis to replace birch ingrowth in the Pukkala et al. (2013) model), which seems excessive. While the same optimal management regimes are generally obtained with both ecological models – except for single-species stands (see Table 4) – the characteristics of the optimal solutions are affected by the ecological model used. This highlights the need for further developing the ecological models and fine-tuning their description of the growth of Finnish forests.

Another source of imprecision are the properties of the transition matrix model: trees are divided into size classes and forest growth is mainly dependent on stand density. Rämö and Tahvonen (2014) have suggested that transition matrix models overestimate forest growth. Alternatively, using an individual tree model would allow for describing the development of the forest stand in a more sophisticated way, based on the characteristics and interactions of individual trees (Tahvonen, 2011). As the trees in an individual tree model are not divided into fixed size classes, the steady-state size structure computed with a single-tree model deviates from the classic, reverse-J structure (Rämö & Tahvonen, 2014; Tahvonen, 2011). Using an individual tree model could also eliminate some computational complications confronted in this thesis, brought about by each tree only being able to grow a maximum of one size class in each period in the transition matrix model.

The genetic algorithm applied for solving the timing of thinnings caused some technical issues in cases where RF without artificial regeneration was optimal. In computational terms, these solutions are CCF solutions with near-clearcuts. Unlike assumed, the optimal steady-state harvest interval could not be reached within a transition period of seven harvests. Hence, the solutions had to be computed in pieces, such that the harvest timing could be optimized over a time horizon longer than seven harvests, before setting a fixed harvesting interval. Using a reinforcement learning framework instead of the genetic algorithm, as Malo et al. (2021) have done, would allow for optimizing the harvest intervals over a longer time horizon without having to perform several computations.

In light of the results of this thesis, it is clear that neither RF nor CCF is categorically superior in terms of forestry income. As a result, the categorical prohibition of clearcuts, as demanded by the Finnish citizens' initiative (Parliament of Finland, 2019), would impair the profitability of forestry in cases where rotation forestry is the economically optimal management regime. This would at least be the case for pure birch stands in Central and Southern Finland. Further, when the interest rate is low (r = 1%), the management of mixed pine–birch stands in Central and Southern Finland is suggested to be more profitable with near-clearcuts, and rotation forestry is also viable on pure pine stands. On the other hand, when the interest rate is higher (r = 3%), continuous cover management seems suitable for mixed pine–birch stands and pure pine stands of Central and Southern Finland. While this thesis suggests that with realistic interest rates, CCF is a viable management strategy much more often than forest owners realize, there are still cases where RF is more profitable. Further, in this thesis results were computed from bare land. However, the viability of CCF may deteriorate if the initial state of the forest stand is far from the optimal steady state, or it may be optimal to clear-cut once before switching to CCF (Tahvonen & Rämö, 2016). Hence, it is better to optimize the suitable regime case by case, while considering the previous management activities, growth conditions and tree species in the forest stand.

In this thesis, the optimal regime and other management choices have been studied purely from the viewpoint of maximizing net revenues from timber production. However, in a world where forests also provide other ecosystem services (Brockerhoff et al., 2017) and where forest management has ecological impacts in itself (Duncker et al., 2012), successful forest management requires the harmonising of a number of objectives. Previous economic-ecological optimization literature has shown that the ranking of favourable management regimes at the stand-level can change when ecological objectives are included. Taking climate change mitigation into account increases the favourability of CCF (Assmuth et al., 2021; Parkatti & Tahvonen, 2021) and mixed-species management over monocultures (Assmuth et al., 2021). The same happens when values of other ecosystem services (such as biodiversity) are included as one of the forest management objectives (Pukkala, 2016; Tahvonen et al., 2019). Eyvindson et al. (2021) studied, how restricting RF or CCF affects forest multifunctionality at the landscape level. They concluded that while CCF should be recommended as the primary management alternative, prohibiting clearcuts would not improve multifunctionality in terms of environmental and recreational ecosystem services. Hence, a categorical prohibition of clearcuts does not seem advisable even in regard to non-timber values.

Economic-ecological research on the optimal management regime choice in Nordic conditions has taken significant steps forward in recent years. Yet, the understanding remains incomplete. Future research could take other ecosystem services, such as climate change mitigation, adaptation and biodiversity, into account when optimizing the management of mixed pine–birch stands. Further, the unprecedented warming of the climate is predicted to affect the development of boreal forests in the future – not only through rising temperatures but also through more frequent forest disturbances (IPCC, 2019). Hence, a relevant model extension would allow for variable biological parameters, such as an increasing temperature sum over time. Future research questions also involve the impacts of stochasticity of forest stand development on the optimal solutions in pine–birch stands.

5 Conclusion

This thesis studied the economically optimal management regime and species composition of boreal mixed-species forest stands with Scots pine (*Pinus sylvestris* L.) and silver birch (*Betula pendula* Roth) in Central and Southern Finland. In terms of optimal management regime choice, this was the first research of its kind for this species combination. The analysis was based on an economic model that maximizes the net present value of forestry income, and determines the optimal regime endogenously and flexibly, by optimizing both the rotation period and the timing and intensity of thinnings. The model is theoretically sound and generalized, and all model details are empirically estimated. Forest stand development was described by size-structured empirical growth models by Pukkala et al. (2011, 2013) and by Pukkala et al. (2021), of which the latter has not been used in this line of analysis before. Using the optimization results, this thesis discussed whether economic-ecological optimization supports the objective of avoiding clearcuts, desired by a recent citizens' initiative in Finland (Parliament of Finland, 2019) and the new EU forest strategy for 2030 (European Commission, 2021b).

The optimization results in this thesis show, for the first time empirically, that it can be optimal to conduct near-clearcuts without investing in artificial regeneration afterwards, as theoretically presented by Tahvonen (2015). Near-clearcuts create favourable conditions for abundant ingrowth by lowering the stand basal area; it is hence profitable to solely utilize the unharvested young trees and natural regeneration in generating a new tree cohort. This management strategy is found to be suitable for pure birch stands due to the early successional and light-demanding nature of birch (Hynynen et al., 2010). Rotation forestry without artificial regeneration is also optimal for mixed pine–birch stands when the interest rate is low (r = 1%) and the stand is dominated by birch. With higher interest rates (r = 3%), continuous cover forestry becomes optimal for mixed stands. Continuous cover management of pure pine stands is found to be more viable than in previous optimization studies (cf., Parkatti et al. 2019; Parkatti & Tahvonen, 2020). Even though neither management regime is categorically superior in terms of forestry income, there are many cases where the environmental and recreational benefits of CCF (Díaz-Yáñez et al., 2020; Eyvindson et al., 2021) can be taken advantage of while simultaneously maximizing timber revenues.

The optimization results indicate that it is economically beneficial to let birch regenerate in a pine stand and even dominate it, due to improvements in overall ingrowth. Hence, improving the potentially low quality of pine wood in pure pine *MT* forest sites by mixing it with birch (Hynynen et al., 2010; Äijälä et al., 2019) is suggested to be an economically viable management strategy. Further, in light of the cases studied in this thesis, increasing tree species diversity for its ecological benefits (Gamfeldt et al., 2013; Gauthier et al., 2015; Hynynen et al., 2010) is even optimal with respect solely to timber revenue. However, it is noted that the details of the optimal solutions are dependent on the ecological model used.

The results of this thesis suggest that the fear of economic losses from avoiding clearcuts has been inflated and is, in some cases, baseless: even in the sole context of timber revenue, CCF is a feasible alternative to RF, and avoiding clearcuts can be economically beneficial. Consequently, the Finnish citizens' initiative and the new EU forest strategy can be said to provide some good guidelines for improving the management of boreal forests, even economically. Moreover, the Finnish Parliament's recent objective to increase the share of CCF in state-owned forests (Agriculture and Forestry Committee, 2021) seems economically sensible – not to mention the potential of the regime shift in providing ecosystem services other than timber production (Díaz-Yáñez et al., 2020; Eyvindson et al., 2021).

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Appendices

Appendix 1. Size class -specific parameter values for pine and birch according to Heinonen (1994).

			Pine		Birch	
Size class	γ_s	d_s	v_{1s1}	v_{2s1}	v_{1s2}	v_{2s2}
1	0.0005	2.5	0	0	0	0
2	0.0044	7.5	0	0.03458	0	0.01591
3	0.0123	12.5	0	0.06659	0	0.07464
4	0.0241	17.5	0.09764	0.10166	0	0.18005
5	0.0398	22.5	0.27034	0.03905	0.25137	0.07854
6	0.0594	27.5	0.48515	0.03001	0.45137	0.06655
7	0.0830	32.5	0.74205	0.02750	0.69732	0.05827
8	0.1106	37.5	1.04106	0.02647	0.96304	0.04978
9	0.1419	42.5	1.38216	0.02596	1.24859	0.04865
10	0.1772	47.5	1.76537	0.02567	1.55035	0.04463
11	0.2165	52.5	2.29067	0.02549	1.86531	0.03891

Note: γ_s, basal area of a tree (m^2); ds, d_s diameter at breast height; v_{1sj}, sawtimber volume (m3) per tree; v_{2sj}, pulpwood volume (m^3) per tree. Tree volume is the sum of sawlog and pulpwood volumes.

Appendix 2. Species-specific parameter values for harvesting costs functions.

Species	i	C_{ji0}	C_{ji1}	C_{ji2}	C_{ji3}	C_{ji4}	C_{ji5}
Pine	*th*	2.415	0.547	0.196	0.308	2.272	0.535
	cl	2.100	0.532	0.196	0.308	1.376	0.393
Birch	*th*	2.415	0.420	0.797	0.174	2.272	0.535
	cl	2.100	0.430	0.756	0.174	1.376	0.393

Note: th = thinning, cl = clearcut.

Appendix 3. Species-specific regression coefficients for ecological models.

Pukkala et al. (2013)			Pukkala et al. (2021)		
a_i	Pine	Birch	b_i	Pine	Birch
0	-5.9901	-6.0405	0	-7.1552	-8.6306
1	0.5057	0.9309	1	0.4415	0.5097
2	-0.07699	-0.1441	2	-0.0685	-0.0829
3	0.987	0.812	3	1.1198	1.3163
4	-0.3593	-0.1424	4	-0.2027	-0.3864
5	-0.141	-0.03275	5	-0.1236	0
6	-0.1797	-0.1554	6	0	-0.0545
7	0	-0.1137	7	0	0.0253
8	0	0.004857	8	1.41223	1.60895
9	2.333	0.433	9	1.8852	0.71578
10	1.518	2.284	10	-0.21317	-0.08236
11	-0.083	-0.217	11	-0.25637	0
12	-0.602	0	12	0	-0.04814
13	-0.332	0	13	0	-0.13481
14	0	-0.266	14	0	1.40145
15	6.61	6.933	15	-6.6933	-3.2919
16	-0.844	0	16	1.9051	1.5438
17	0	0.496	17	-0.5035	-1.292
18	0	-0.161	18	0	0.9436
19	-0.375	∞			
20	1.045	0			
21	-0.556	0			