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Economics of Multifunctional Forestry in the Sámi People Homeland Region

Vesa-Pekka Parkatti, Olli Tahvonen

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By Vesa-Pekka Parkatti, University of Helsinki
Olli Tahvonen, University of Helsinki

Summary

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Keywords: Arctic Forestry, Indigenous Peoples, Sámi, Continuous Cover Forestry, Uneven-Aged Forestry, Carbon Sequestration, Reindeer Husbandry, Carbon Debt, Payback Period

JEL Classification: Q2, Q23, Q24, Q28

Address for correspondence:
Olli Tahvonen
University of Helsinki
Department of Forest Sciences, Department of Economics
P.O. Box 27
FI-00014 Helsinki
Finland
E-mail: olli.tahvonen@helsinki.fi

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Vesa-Pekka Parkatti

Department of Forest Sciences, Department of Economics, University of Helsinki,

P.O. Box 27, FI-00014 Helsinki, Finland

E-mail: vesa-pekka.parkatti@helsinki.fi

Olli Tahvonen

Department of Forest Sciences, Department of Economics, University of Helsinki,

P.O. Box 27, FI-00014 Helsinki, Finland

E-mail: olli.tahvonen@helsinki.fi

Abstract

We study forestry in the Sámi people homeland region to understand an ongoing conflict between conventional forest logging and maintaining forests as reindeer pastures for indigenous people. We use a detailed model that simultaneously includes timber production, carbon storage in living biomass, deadwood and wood products, negative effects on reindeer husbandry, and a flexible optimization between rotation forestry (cf. clearcuts) and forestry that maintains continuous forest cover. We show that the profitability of conventional forestry is based on utilizing existing forest stands, an outcome that can be understood as forest capital mining. By varying the carbon price between €0 tCO_2 and €40 tCO_2, we show that the optimal solutions based on a 3% interest rate are always continuous cover forestry. A carbon price of $€60-€100 tCO_2^{-1}$ implies that it is optimal to give up timber production and utilize forests for carbon storage and reindeer pasture only. Given the present forest management practices and an old-growth forest as the initial state, the carbon choke price decreases to €14–€20 CO_2^{-1}. The optimal choice between timber production and utilizing forests purely for carbon storage and reindeer husbandry may depend on the initial forest state. The choice between maintaining old-growth forest and converting land to timber production, as determined by dynamic economic analysis, is incompatible with the frequently applied approach based on carbon debt and the carbon payback period.

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1 Introduction

Forests are a prime example of natural resources that offer numerous contributions beyond their extractive values. These values should be included in economic analyses of forest resources despite any difficulties in quantifying their typically nonmarket realizations. The setup becomes potentially more complicated in situations where forests are concurrently vital to indigenous cultures and industrial-scale timber demand. According to some estimates, various indigenous groups manage 11% of the world's forests and 80% of its biodiversity (Trosper and Parrotta 2012). Highly divergent views on forestry occur on every continent, and examples include industrial logging practices vs. First Nations multi-use traditions in Canada, forest-related cultures and timber extraction in India, and traditional multipurpose forest management vs. pulp plantations in Latin America (Trosper et al. 2012, Ramakrishnan et al. 2012, Gabay et al. 2012). The Sàmi people are the only indigenous people in the European Union, where they populate the northernmost parts of Finland, Sweden, Norway, and northwestern Russia. Long-lasting conflicts have occurred between these reindeer herders and government-operated forestry (Vihervaara et al. 2010). We show that finding solutions for this conflict may benefit from profitability estimates of the present industrial forestry practices vs. other forest management alternatives and from the simultaneous inclusion of nonmarket values such as carbon storage and external effects on land use by indigenous people. We conjecture that sharpening the economic analysis of forestry may help to reach reconciliation in other parts of the world as well.

According to Ruppert et al. (2016) and Martin et al. (2017), industrial forest management practices have contributed to forest fragmentation and loss of old growths in the Canadian boreal region. As a result, the woodland caribou is listed as a threatened species throughout many regions. The authors develop a spatial optimization approach that meets the fixed industrial wood quantity targets but aims to minimize the negative effects of high-quality woodland caribou habitat. Interestingly, their results show that the optimized spatial allocation of logging may create a major increase (30%) in suitable caribou habitat. However, from the economic viewpoint, their setup is not fully flexible and leaves open the social optimality of existing industrial logging targets and the monetary implications of various spatial logging solutions. In contrast to this setup, Malcolm et al. (2020) study the conversion of Canadian primary forest landscapes to managed timber production. According to their results, clearcut logging leads to long-lasting carbon debt and, compared to other harvesting methods or conservation, is questionable from the viewpoint of climate change mitigation. We remark that the analysis of carbon debts and payback periods that originate from Fargione et al. (2008) can be questioned from the economic point of view, as it ignores prices, costs, interest rate, and any kind of optimization. In contrast to these studies, we analyze wood production and other forest purposes by applying a systematic economic and interdisciplinary setup.

The forests in Finnish upper Lapland mostly consist of pure Scots pine (Pinus sylvestris L.) stands, are characterized by high government ownership (70%), and are managed by a state-owned enterprise. The harsh climate conditions cause forest growth to be slow, averaging ca.1.5 m^3 per hectare per year (Natural Resources Institute Finland 2018b). Hyppönen (2002) estimates the yearly net income per hectare in the Lapland region and finds it to only be ca. 10% of the income in southern Finland. This estimate is not based on detailed economic analysis but as such it supports studying the profitability of industrial timber production in upper Lapland and how it is able to compete with other forest functions, i.e. reindeer husbandry, tourism, conservation, hunting, and berry/mushroom picking (Ahtikoski et al. 2011, Hallikainen et al. 2008), which are not directly supported by market incentives.

Semi-domesticated reindeer husbandry is an integral part of the Sàmi livelihood and culture, as they are the only indigenous people recognized in the constitutions of Finland, Norway, Sweden, and the European Union (European Union 2005). Finnish legislation on reindeer husbandry (Reindeer Husbandry Act 848/1990) states that other land-use forms should not cause remarkable disadvantage to reindeer husbandry on the government lands of upper Lapland. The disadvantage level is difficult to measure, and the problem is compounded by the fact that while the effect of each forest logging operation on reindeer pastures may be minor, their cumulative effect over time may become high.

Reindeer husbandry is organized by cooperatives and approximately 35% of the forests in certain cooperative areas have been logged during the last 50 years, with negative effects on reindeer husbandry (Saijets 2019). Our aim is to increase the understanding of the nature of this trade-off.

According to the guidelines for public forests in the Sámi people homeland regions, forestry should mainly be conducted as rotation forestry (RF), as thinning of small-diameter trees ("thinning from below"), and as regeneration by seedling felling. Thinning small-diameter trees contrasts with numerous economic studies on Scots pine stands (Tahvonen et al. 2013, Tahvonen 2015), where thinning large size classes ("thinning from above") is optimal. Seedling felling is close to clearcutting, and Tahvonen and Rämö (2016) show that the economic competitiveness of continuous cover forestry (CCF) compared to clearcuts increases as growth conditions decrease. Assmuth et al. (2018) show that pricing carbon favors CCF, when simultaneously optimizing both timber production and carbon sequestration. This leads us to ask how flexible management alternatives, such as thinning from above and CCF together with carbon storage and externalities on reindeer husbandry, determine socially preferable forestry in upper Lapland. Our analysis with thinning and CCF vs. RF optimization extends the common economic approach that typically relies on some variant of the classic optimal rotation model (Samuelson 1976, Strang 1976, Van Kooten et al. 1995).

We analyze the profitability of forest management by applying a statistical-empirical size-structured model that allows the joint optimization of wood production and carbon sequestration, including carbon in wood products and dead trees. The model allows completely flexible optimization between RF and CCF. Reindeer husbandry is included by calculating the negative effect of logging on reindeer pastures by utilizing available results of their economic value (Tahvonen et al. 2014).

When optimizing timber production only and assuming a 1% interest rate, the optimal management regime is RF with a very long rotation length, while a 3% interest rate causes CCF to become optimal when thinning large-diameter trees. Adding optimal carbon sequestration lengthens the optimal rotation, optimal CCF steady-state harvesting intervals, directs harvests to larger trees, and increases the mean stand volume toward levels that are more favorable to reindeer husbandry. Furthermore, a high enough carbon price causes harvesting to stop completely, and it becomes optimal to utilize forest solely as carbon storage (and reindeer pasture). While such an outcome is known to be possible in the generic optimal rotation model, we extend the result to CCF.

In addition to studying optimal forest management solutions, we analyze the consequences of conventional forest management by following silvicultural guidelines that are applied on public lands in the Sàmi homeland region. We show that the positive net present value of conventional forest management is based on harvesting existing forests that, in most cases, are "free gifts of nature", i.e. have generated without any management effort. Activities aiming to continue timber production by active management actions, e.g. seed tree felling, yield negative bare land values (BLV) if the interest rate is 2% or higher. Because of the questionable economic sustainable properties, we label this form of forest management as "forest capital mining". Switching from conventional forest management to thinning from above, longer rotations, and CCF would increase the profitability of forestry, maintain timber yield, and offer a possible starting point for integrating forestry, carbon storage, and the maintenance of reindeer pasture conditions. A carbon price equal to $€14 tCO_2^{-1}$ or higher is enough to imply that utilizing an existing old-growth forest solely as carbon storage becomes superior compared to timber production that follows the existing silvicultural guidelines.

Finally, we compare our economic setup and the approach of extensive literature initiated by Fargione et al. (2008), which applies the concepts "carbon debt" "payback period" to understand the tradeoff between forest plantations and maintaining old-growth forests. It turns out that the frequently applied carbon debt and payback period analysis is fundamentally incompatible with a dynamic economic approach on land conversion of old-growth forests to timber production.

2 Optimizing timber production and carbon storage

Let the number of trees in a size class s, at the beginning of period t, be denoted by $x_{st}, s = 1,...,n, t = t_0, t_0 + 1,..., T$ and write $\mathbf{x}_t = x_{1t}, x_{2t},..., x_{nt.}$. The fraction of trees that move to the next size class during each period t is $0 \le \alpha_s(\mathbf{x}_t) \le 1, s = 1,...,n-1$. Similarly, the fraction of trees that die during each period is denoted as $0 \le \mu_s(\mathbf{x}_t) \le 1, s = 1,...,n.$. Thus, the fraction of trees that stay in the same size class during a period t is $1-\alpha_s(\mathbf{x}_t) - \mu_s(\mathbf{x}_t) \ge 0$. The number of trees harvested from a size-class s at the end of a period t is $h_{st}, s = 1,...,n, t = t_0, t_0+1...,T$. Write $\mathbf{h}_t = (h_{1t}, h_{2t},...,h_{nt})$. In addition, let $\phi(\mathbf{x}_t)$ describe the ingrowth of trees (natural regeneration) into the smallest size class. The stand develops according to the difference equation system

$$x_{1,t+1} = \phi(\mathbf{x}_t) + [1-\alpha_1(\mathbf{x}_t) - \mu_1(\mathbf{x}_t)]x_{1t} - h_{1t}, \; t = t_0,...,T \tag{1}$$

$$x_{s+1,t+1} = \alpha_s(\mathbf{x}_t)x_{st} + [1-\alpha_{s+1}(\mathbf{x}_t) - \mu_{s+1}(\mathbf{x}_t)]x_{s+1,t} - h_{s+1.t}, \; s=1,...,n-1, \; t=t_0,...,T. \tag{2}$$

We use seven size classes based on diameter breast height d_s, $s=1,...,7$, ranging from 75 mm to 375 mm (midpoint) by 50 mm intervals. Each size class s has specific sawlog and pulpwood volumes given by v_{1s} and $v_{2s}, s = 1,...,7.$, respectively (Appendix A, Table A1). These size-class specific sawlog and pulpwood volumes correspond to volumes in the Finnish Motti stand simulator (Malata et al. 2003). Local roadside prices (€/m^3) for sawlog and pulpwood are denoted by p_1 and p_2, respectively (Appendix A, Table A2). The revenues per harvest $R(\mathbf{h}_t)$ are specified as

$$R(\mathbf{h}_t) = \sum_{s=1}^{n} (v_{1s}p_1 + v_{2s}p_2)\, h_{st}. \tag{3}$$

Following Nurminen et al. (2006), separate variable harvesting costs for thinning C_{th} and seedling felling C_{sf} are given as

$$C_i = C_{i0}C_{i1}\sum_{s=1}^{7} h_{st}\left(C_{i2} + C_{i3}v_s - C_{i4}v_s^2\right) + C_{i5}\left[C_{i6}\sum_{s=1}^{7} h_{st}v_s + C_{i7}\left(\sum_{s=1}^{7} h_{st}v_{st}\right)^{0.7}\right], \; i = th, sf. \tag{4}$$

The parameter values $C_{is}, i = th, sf, s = 1,...,7$ are specified in Appendix A, Table A3 and imply that harvesting costs are higher in thinning compared to seedling felling. We also include fixed costs of harvesting (C_f = €250 ha^{-1}) that consist of both the transportation of the logging machinery and harvest operation planning costs. The fixed cost is set smaller compared to e.g. Parkatti and Tahvonen (2020) because of larger average forest management unit in upper Finland.

Based on the silvicultural recommendations of Metsähallitus (2014) for Sàmi homeland regions, we specify the model to describe seed regeneration and seedling felling. Thus, the initial stand consists of 50 seed trees in size class 22.5cm and 30 trees in size class 27.5 cm. These trees have been left unharvested in the previous seedling felling to generate new saplings. We assume that these seed trees are harvested 25 years after seedling felling. After taken into account the growth of these trees during the 25-year period, their stumpage price equal $1512€\, ha^{-1}$.

Seed tree regeneration requires some active management effort, i.e. harrowing at $t = 0$ and tending of the seedling stand at $t = 25$. Based on the most recent statistics available, we set these cost equal to €169 ha^{-1} and €385 ha^{-1} respectively (Natural Resources Institute Finland 2014).

Clearcuts and seedling felling affects forest as reindeer pasture because of decreases in both ground lichen and arboreal lichen (lichen growing in trees) that are both important winter forage for reindeer (Pekkarinen et al 2015). Based on an expert estimate by Kumpula (2017, personal communication) we assume that the decrease of both ground and arboreal lichen biomass after seedling felling is 80% for the first 30 years and 50% up to 80 years. This estimate is based on studies applying satellite observations and field measurements on lichen biomass and on reindeer movements in various forest sites (Kumpula et al. 2007, 2014). In Jonsson Čabrajič et al. (2010) and Sandström et al. (2016) the optimal tree density for ground lichen may be about $10-15m^2ha^{-1}$. According to the forest growth model applied here, the $15m^2$ density is reached 65 years after seedling felling. After recognizing that lichen density reacts to changes in growing conditions with a delay, this estimate is in line with our assumption on the effects of felling on lichen availability. The economic value of an old-growth forest hectare with lichen biomass is approximately €30 ha^{-1} per year (Tahvonen et al. 2014, Pekkarinen et al. 2015, 2020). This allows us to include an approximation for the external effects of seedling felling on reindeer husbandry by the inclusion of €1056 (interest rate 1%) or €629 (interest rate 3%) in the costs occurring after seed tree felling.

The existence of fixed cost of harvesting in both thinning and seedling felling implies that we must include a binary variable $\delta_t : Z \in \{0,1\}$, $t = t_0,...,T$ and define both harvests and fixed costs of harvesting by Boolean operators $h_{st} = \delta_t h_{st}$ and $C_f = \delta_t C_f$, respectively. When $\delta_t = 1$, a fixed cost C_f occurs and h_{st} is freely optimized. In contrast, when $\delta_t = 0$, both C_f and h_{st} equal zero.

In addition to timber revenues, we include social value of carbon sequestration applying the specifications in Assmuth et al. (2018). Let $p_c \geq 0$ denote the social price of carbon in €tCO_2^{-1}. Total commercial stem volume at the beginning of period *t* is denoted by $\omega_t = \sum_{s=1}^{n} x_{st}\left(v_{1s} + v_{2s}\right)$. This is converted into stem dry mass using a density factor $\rho = 0.3729$ in tons per m^3. (Lehtonen et al. 2004). The stem dry mass is converted to whole tree dry mass (including foliage, branches, bark, stumps and roots) by an expansion factor $\eta = 1.8909$ (Lehtonen et al. 2004). Thus, the total stand biomass equals $\rho\eta\omega_t$ in tons of dry mass. The carbon content of one ton of dry mass is given by $\theta = 1.8333$ in CO_2 (Pihlainen et al. 2014). The dry mass content in sawlog and pulpwood harvests are denoted by $y_{1t} = \rho\sum_{s=1}^{n} h_{st} v_{1s}$ and $y_{2t} = \rho\sum_{s=1}^{n} h_{st} v_{2s}$, respectively. Dead tree matter of the stand consists of both naturally died trees and harvesting residues. The dry mass of dead tree matter from natural mortality is $y_{3t} = \rho\eta\sum_{s=1}^{n} \mu_s(\mathbf{x}_t) x_{st}\left(v_{1s} + v_{2s}\right)$ and the dry mass of harvest residue is $y_{4t} = \left(\eta - 1\right)\left(y_{1t} + y_{2t}\right)$. Let g_j, $j = 1,2,3,4$ present the annual decay rates of sawlog, pulpwood and dead tree matter, respectively. The decay rates are set to $g_1 = 0.0706$, $g_2 = 0.4707$ (Liski et al. 2001) and to compute the parameter $g_3 = g_4 = 0.1019$ we apply Mäkinen et al. (2006), Palviainen et al (2004, 2010) and Shorohova et al. (2008). The present value of future emissions from product and dead tree mass decay are given by

$p_c\beta_{rj}$ where $\beta_{rj} = g_j / (g_j + r)$, $j = 1,...,4$ (Assmuth et al. 2018) where r is the annual rate of interest. Thus, the economic value of the net carbon sequestration at $t = t_0,...,T$ is

$$Q(\mathbf{x}_t, \mathbf{h}_t) = p_c\theta\left[\rho\eta(\omega_{t+1} - \omega_t) + \sum_{j=1}^{4}(1 - \beta_{rj})y_{jt}\right]. \tag{5}$$

Denote the period length by Δ and the discount factor by $b^\Delta = 1/(1+r)^\Delta$. Let W denote the present value of harvesting the seed trees net of the cost of harrowing and tending of the seedling stand and the external cost of reindeer husbandry. Taken together, the problem is to

$$\max_{\{h_{st}, \delta_t, T \in [t_0, \infty)\}} J = \frac{W + \sum_{t=t_0}^{T}[R(\mathbf{h}_t) - C_{th}(\mathbf{h}_t) - C_{sf}(\mathbf{h}_t) - \delta_t C_f]b^{\Delta(t+1)} + \sum_{t=0}^{T} Q(\mathbf{x}_t, \mathbf{h}_t) b^{\Delta(t+1)}}{1 - b^{\Delta(T+1)}} \tag{6}$$

subject to (1),(2) and

$$h_{st} = \delta_t h_{st},\ s = 1,...,n,\ t = t_0,...,T \tag{7}$$

$$x_{s,T+1} = \hat{x}_{s,T+1},\ s = 1,...,n \tag{8}$$

$$x_{s,t_0} \text{ given, } s = 1,...,n, \tag{9}$$

where $T \in [t_0, \infty)$ and the non-negativity conditions $x_{st} \geq 0, h_{st} \geq 0, t = t_0,...,T, s = 1,...,n$ must hold. Restriction (8) specifies the seed trees left at the end of rotation and following the recommendations by Metsähallitus (2014) we require 80 seed trees to be left at the seedling felling at T by and specify (8) as $\hat{x}_{s,T+1} = 0$, s=1,2,3,6,7, $\hat{x}_{4,T+1}$=50 and $\hat{x}_{5,T+1}$=30. At t_0 (45 years) the stand state is given as $\mathbf{x}_{t_0} = [1750, 0, ..., 0]$, i.e. the stand consists of 1750 trees in 7.5 cm diameter class.

3 Forest growth models and calibration

3.1 Ecological growth model for a pure Scots pine forest

Potentially suitable and openly published ecological models with natural regeneration for Fennoscandian forests are the models by Bollandsås et al. (2008) and Pukkala et al. (2013). Both models include parameter values that allow model calibration for different growth conditions. In what follows we present the properties of the model by Bollandsås et al (2008) since a calibrated version of their model will be applied in optimization.

The proportion of size class s trees moving to size-class $s+1$ during the next 5-year period in the Bollandsås et al. (2008) model is given as:

$$\alpha_s(\mathbf{x}_t) = q^{-1}(25.543 + 0.0251\, d_s - 5.660 \cdot 10^{-5}\, d_s^2 - 0.216\beta_s(\mathbf{x}_t) + 0.698SI - 0.123\, \beta(\mathbf{x}_t) - 0.336\, LAT \qquad (10)$$

where $\alpha_s(\mathbf{x}_t)$ is obtained by dividing the 5-year diameter growth (mm) of a size class s by the width of the size-class q (50 mm) (Bollandsås 2008). The basal area of the stand (m^2 ha^{-1}) is denoted by β and specified as either $\beta(\mathbf{x}_t) = \sum_{s=1}^{n} \gamma_s x_s$ (symmetric competition) or $\beta_s(\mathbf{x}_t) = \sum_{i=s+1}^{n} \gamma_s x_s, s = 1.., n-1$ (asymmetric competition) where γ_s is the basal area (m^2) of a single tree in a size class s. Parameter LAT (latitude) set to 69.36 °N, to represent Finnish upper Lapland. The parameter SI is the height (m) of the dominant trees at the stand age of 40 years. The proportion of trees in a size-class s that die due to natural mortality in the next 5-year period according to the Bollandsås et al. (2008) is given as:

$$\mu_s(\mathbf{x}_t) = \left[1 + \exp(-(-1.808 + 0.027d_s + 3.300 \cdot 10^{-5} d_s^2 + 0.055\beta(\mathbf{x}_t)))\right]^{-1} \qquad (11)$$

Finally, the number of naturally regenerated trees that grow into the smallest size-class (ingrowth) during the next 5-year period according to the Bollandsås et al. (2008) model is given as:

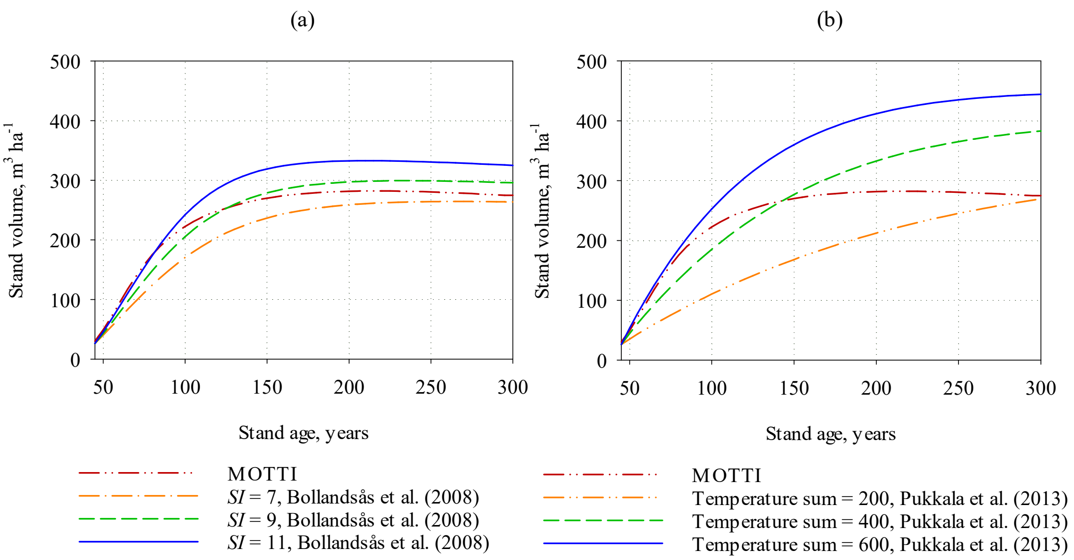
$$\phi(\mathbf{x}_t) = \frac{67.152\beta(\mathbf{x}_t)^{-0.076}}{1 + \exp(0.452 + 0.062\beta(\mathbf{x}_t)))} \qquad (12)$$

3.2 Model calibration

We calibrate the model by Bollandsås et al. (2008) applying output data from a Finnish Motti stand simulator for an average fertility pine stand (*Vaccinium type)*. The Motti stand simulator is a widely used decision-support tool by the Natural Resources Institute Finland (Salminen et al. 2005). It is based on large inventory data sets covering the whole of Finland (Matala et al. 2003) but since the source code is not fully open, we cannot use the model directly for optimization purposes.

We specify the Bollandsås et al (2008) model *SI* parameter in order to obtain the volume development to represent the volume development of the Motti stand simulator (without thinning). Since Motti does not include ingrowth, we set ingrowth (3) to zero in calibration. Similar calibration is performed for Pukkala et al. (2013) model by applying a range of different temperature sums[1]. Figure. 1b shows that the Pukkala et al. (2013) model does not produce a long-term stand volume development similar to the development by Motti. Figure 1a shows that the stand volume development with Bollandsås et al. (2008) model and *SI* of 9 m is initially slightly lower and in a long run slightly higher compared to the stand volume development produced by Motti. However, overall, the stand volume developments are closest by setting $SI = 9m$.

When the stand volume developments in Figures 1a,b are compared to actual stand volumes in Upper Lapland old growth forests, they turn to be rather high since highest per hectare volumes fall below $200m^3ha^{-1}$ (Paikkatietoikkuna 2017). The difference may follow from the fact that Motti simulates managed forests, while the present actual old growth forests are naturally generated without active management.



Figures. 1a,b: Comparing stand volume developments of Bollandsås et al. (2008) (a) and Pukkala et al. (2013) (b) models to the development by Motti stand simulator.
Note: *SI* = height of dominant trees at the age of 40 years.

[1] For applying the Pukkala et al. (2013) model see Parkatti et al. (2019) and Parkatti and Tahvonen (2020).

Figures. 2a–c show the characteristics of the calibrated Bollandsås et al. (2008) model and in Figure 2a trees reach their peak growth at approximately 22.5 cm in diameter and that the effect of asymmetric competition (shading of large trees) on diameter growth is large. The probability of natural mortality decreases as a tree grows (Figure. 2b). Ingrowth (natural regeneration) increases as stand basal area decreases albeit ingrowth remains low (Fig. 2c).

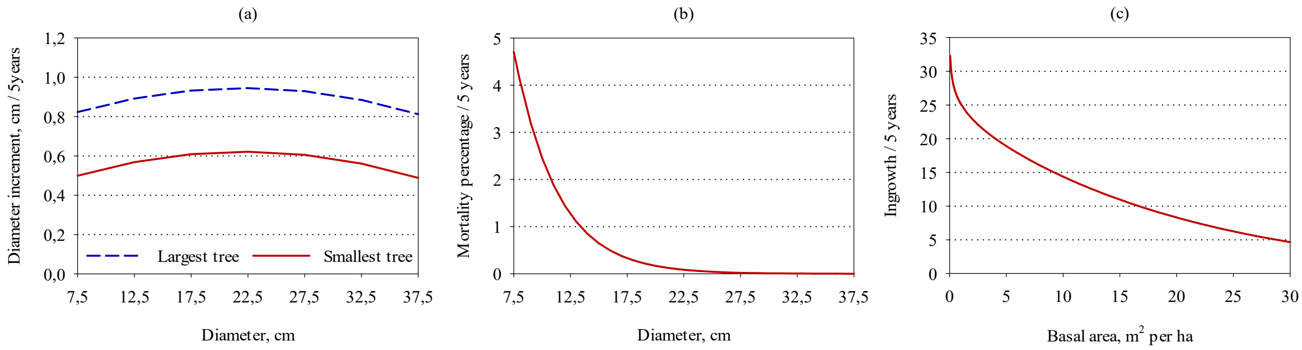


Fig. 2a–c: Scots pine diameter increment (a), mortality (b) and ingrowth (c) with the calibrated Bollandsås et al. (2008) model.
Note: Basal area in (a) and (b) equals 15 m^2 ha^{-1}.

4 Computational methods

The optimization problem (1) – (2) and (6) – (9) is a tri-level problem, in which the choice of rotation length T is the highest-level problem, optimizing harvest timing $\delta_t : Z \in \{0,1\}, t = t_0, t_0 + 1, \ldots$ the middle-level problem and size-class specific harvesting intensity decisions $h_{st}, s = 1,\ldots,n, t = t_0, t_0 + 1, \ldots$ the lowest-level problem. The optimization is carried out using AMPL programming language and Knitro optimization software (version 10.3). Given a rotation length *T*, harvest timing is solved by using genetic and hill-climbing algorithms, while the harvesting intensities are solved with Knitro gradient-based methods. If the maximum net present value is found between $T \in [80, 250)$ the optimal rotation is taken as finite and the management regime as RF. In contrast, if the net present value does not saturate when *T* is increased, the optimal solution is CCF. The optimal infinite time CCF solution is computed by optimizing up to seven transition harvests (both timing and intensities) before reaching an optimized steady state harvesting interval. Using an Intel ® Xeon ®

E5-2643 v3 @3.40GHZ, 24 logical processors computer, the approximation of the infinite horizon solution takes approximately 12 hours to solve.

5 Results

5.1 Economically optimal solutions without thinning

We first solve optimal rotation without thinning, as a reality check, and to obtain a simple reference point for solutions with optimized thinning. In Table 1, increasing interest rate shortens, while increasing carbon price lengthens optimal rotation in line of both theoretical studies and earlier studies applying empirical models (van Kooten et al. 1995, Pihlainen et al. 2014). Higher carbon price increases the total net present value while the net present value from timber production decreases. With a 3% interest rate, a carbon price of €40 tCO_2^{-1} causes the optimal rotation to become infinitely long i.e. forest is utilized solely as carbon storage. When interest rate equals 1%, the choke price is €60 tCO_2^{-1}. As the social price of carbon increases, the discounted carbon sequestration increases and obtains a maximum when no harvesting takes place. With optimal finite rotations, the mean annual yield varies between 1.9/m^3 and 2.2/m^3 (Table 1). The average harvesting costs in the economically optimal solutions are €7.5/m^3. This corresponds rather well with the average clearcut harvesting cost of €8.12/m^3 (Strandström 2018) in Finland.

Table 1: Optimal solutions without thinning and external effects on reindeer husbandry.

Interest rate *r*, %	Price of carbon, € CO_2^{-1}	Net present value, € ha^{-1}	NPV from timber production, € ha^{-1}	Discounted CO_2 sequestration, tCO_2 ha^{-1}	Mean annual yield, m^3 ha^{-1}	Rotation, years
3	0	631	631	29	2.2	95
	20	1255	569	34	2.2	120
	40	2021	369	41	0	∞
1	0	3728	3728	70	2.2	110
	20	5269	3603	83	2.2	125
	40	7160	2906	106	1.9	160

As management is based on seed felling and regeneration, the NPVs in Table 1 do not correspond to the BLV in the classic optimal rotation model. Seedling felling leads to 25-year postponement of harvesting the seed trees. During this period, the seed trees (cf. section 2) grow while the net revenues are realized later. Saving the seed trees in seedling felling decreases the net revenue by €1203 but harvesting the seed trees 25 years later yields (undiscounted) revenues equal to €1512. The present value of the latter is included in the NPVs of Table 1, but not the cost of saving the initial seed trees. Thus, the BLVs are obtained by subtracting €1203 from the NPVs of Table 1, i.e. without carbon sequestration and external effects on reindeer husbandry the BLVs equal €2523 and - €572 with interest rates of 1% and 3%, respectively and obtains zero value when interest rate is 2.8%.

No empirical data on the actual BLVs exist but when the value of forests is needed in various official circumstances, the value in Lapland is set to €50-30 ha^{-1} assuming interest rate between 1-2% (Mäki 2013). The average annual net revenues per hectare in the whole Lapland in 2018 was €33-36 (Natural Resources Institute Finland 2018c) while the corresponding figures with 95 and 110 rotation periods in Table are €49 and €57. Additionally timber prices in Upper Lapland ares lower than the average price level in the whole Lapland suggesting that Table 1 figures somewhat overestimate the profitability of pure timber production in Upper Lapland. The reasons behind the difference include the low cost of seed tree regeneration compared to regeneration methods actually applied[2], the high stand growth predicted by the Motti simulation model and the optimization setup applied here.

Table 1 does not yet include the approximation for the external effects on reindeer husbandry. Assuming no carbon sequestration and 1% interest rate, their inclusion decreases the NPV to €2141, and BLV to €938 and lengthens rotation by 5 years. With 3% interest rate, the NPV decreases to $-$€39 and BLV to $-$€1242 but the optimal rotation does not change. Additionally, the carbon prices implying infinitely long rotations decrease to €55 and €35 with 1% and 3% interest rates.

5.2 Timber production and carbon storage with optimal thinning

Next, we present the economically optimal solutions with optimized thinning. Table 2 shows that under 1% interest rate the optimal solutions are always RF, independent on carbon price applied.

[2] The BLV computations for official purposes (Mäki 2013) assume regeneration cost of €1505-€1063 (interest rate 1%) and €1329-€888 (interest rate 3%) depending on whether regeneration is based on seedlings or seeds. The regeneration cost in our computations are €494 and €834 with interest rate equal to 1% and 3%.

Given a 1% interest rate, the optimal rotation without carbon pricing is 215 years. Optimal carbon storage beyond €20 lengthens the optimal rotation, postpones the first thinning and increases the stand volume (Table 2, Figures. 3a–c).

Table 2: Optimal RF and CCF solutions without external effects on reindeer husbandry.

Interest rate, %	Carbon price, $€CO_2^{-1}$	NPV € ha^{-1}	NPV, timber production, € ha^{-1}	Discounted CO_2 sequestration, $tCO_2\ ha^{-1}$	Mean yield, $m^3 ha^{-1} a^{-1}$	Rotation, years
3	0	–/803	–/803	–/30	–/1.3	–/∞
	20	–/1405	–/784	–/31	–/1.6	–/∞
	40	–/2072	–/609	–/37	–/1.4	–/∞
1	0	5040/4938	5040/4938	67/65	2.4/1.6	215/∞
	20	6498/6356	4960/4855	77/75	2.5/1.5	215/∞
	40	8192/8028	4543/4388	91/91	2.4/1.5	235/∞

Note: Values given as RF / CCF, NPV=net present value.

In comparison, with a 3% interest rate, the optimal solutions are CCF, independent of the carbon price (Table 2). When CCF is optimal, the net present value increases without saturation when rotation is lengthen and optimal RF solution does not exist (Tahvonen 2015, Tahvonen and Rämö 2016). Higher carbon price lengthens the steady state harvesting interval and increases the stand volume (Figure 3a–c, Table 3). It is optimal to thin from above, independent on the interest rate and carbon price. With a 3% interest rate, the carbon choke price is ca. $€60\, tCO^{-1}$, i.e. it becomes optimal to give up timber production Recall that without thinning the choke price was €40 tCO^{-1}.

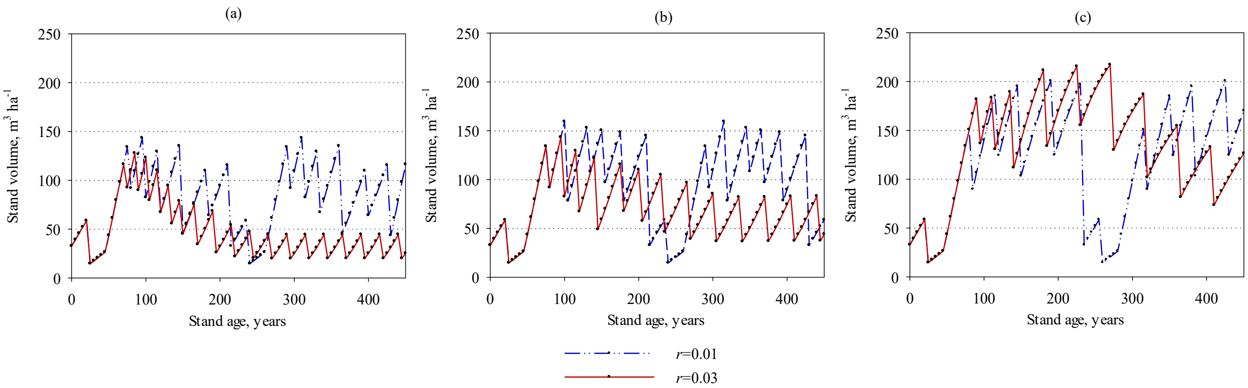
Table 3: Optimal CCF steady states.

Interest rate, %	Carbon price, € tCO_2^{-1}	Mean annual yield, $m^3\ ha^{-1}$	Mean annual timber revenues, € ha^{-1}	Size of harvested trees, cm	Number of trees before / after harvest	Basal area before/after harvest, $m^2\ ha^{-1}$	Mean stand volume, $m^3\ ha^{-1}$	Sawlog ratio of harvested trees, %	Harvest interval, years
3	40	1.4	39	35.0–39.9	364/303	16.6/9.9	112	46	45
	20	1.6	46	25.0–39.9	359/279	11.1/5.1	60	56	35
	0	1.3	34	20.0–39.9	323/248	6.0/3.2	32	60	25
1	40	1.5	45	30.0–39.9	373/284	15.3/7.1	92	48	55
	20	1.5	47	25.0–39.9	368/270	12.5/5.0	66	54	45
	0	1.6	45	25.0–39.9	354/283	10.3/5.2	56	57	30

Including thinning increases the net present values of timber production and without carbon sequestration the increase is 36% and 13% with interest rate equal to 1 and 3% respectively (Tables

1 and 2). Applying the same principles as in the case without thinning, the BLVs are €3837 and −€400 with 1% and 3% interest rates (without carbon pricing).

The average annual net timber revenues with 1% interest rate are €74 ha^{-1} and with 3% interest rate equal to €39 ha^{-1}. Again, these figures are higher than the average annual revenues €33-36 for the whole Lapland region (Natural Resources Institute Finland 2018c) suggesting that our results do not underestimate the profitability of timber production in upper Lapland.



Figures 3a–c. Optimal solutions with €0 tCO_2^{-1} (a), €20 tCO_2^{-1} (b) and €40 tCO_2^{-1} (c) carbon prices for 1% and 3% interest rates.

When our approximation on external cost on reindeer management is included in optimization with thinning, the solution with 1% rate of interest and without carbon sequestration switches to CCF. However, with carbon prices €20-40 and externalities included, the RF regime yields slightly higher NPV compared to CCF. With 3% interest rate, no carbon sequestration but external effects included, the CCF yields −€1029 BLV while with 1% interest rate the BLV is €2641.

5.3 Profitability of conventional forest management

We proceed to study the economics of conventional forest management by following the silvicultural guidelines for public lands in the Sàmi homeland region (Metsähallitus 2014). Given the guidelines and applying our stand growth model, the stand is thinned at the age of 80 years, which decreases the basal area from 21.2 m^2 ha^{-1} to 14.0 m^2 ha^{-1}. According to instructions we thin from below and the number of trees per hectare is decreased from 1333 to 464 and the average arithmetic diameter increases from 13.2 cm to 19.2 cm. Seedling felling is carried out at a stand age of 105 years when the average arithmetic diameter is 22.8 cm (basal area-weighted average diameter equals 25.9 cm). The conventional forest management produces a mean annual yield of 2.2 m^3 ha^{-1}, which is slightly lower than in the economically optimal RF solutions with optimized thinning (Table 2).

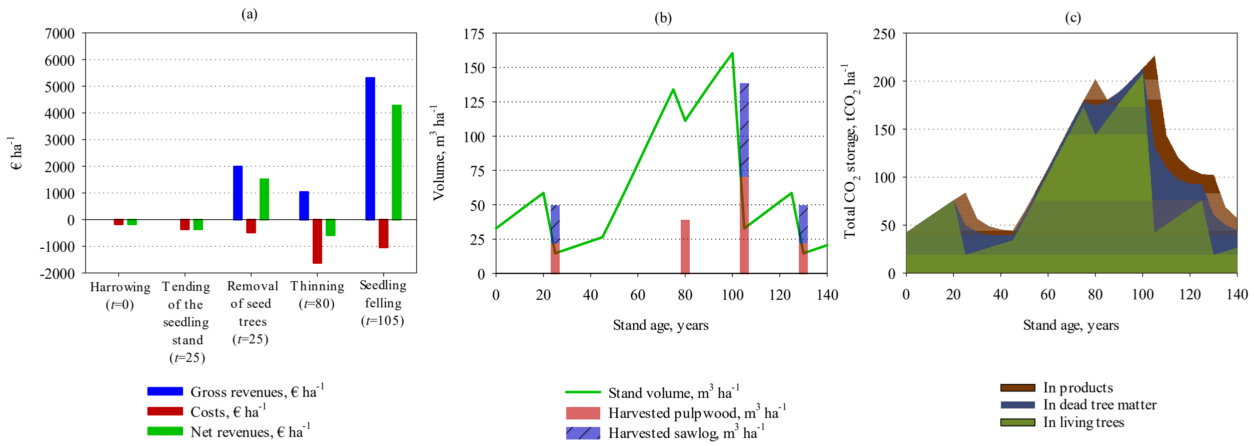


Fig. 4a–c: Revenues and costs (a), stand volume development (b) and carbon storage development (c) in conventional forest management.

As shown in Figure 4a following silvicultural guidelines implies that the immediate net revenues from thinning are negative, i.e. thinning is "non-commercial". Since thinning is targeted to small size classes, the average harvesting costs are €12.1/m^3, which are higher compared to the economically optimal (thinning from above) solutions (€8.0/m^3), but rather close to the average reported harvesting costs in Finland (€10.59/m^3) (Strandström 2018).

The NPVs from conventional forest management, €3100 and €530 with interest rate of 1% and 3% are lower the economically optimal solutions with and without optimized thinning. This is not surprise since thinning from above has been found economically superior to thinning from below in economic studies (Tahvonen et al. 2013). With a 3% interest rate the NPV remains positive by the revenues of €722 from harvesting the initial seedling trees at year 25. The BLVs from conventional forest management equal €1807 and −€673 with interest rates 1% and 3%. The average annual net revenue is €44 ha^{-1} and still above the empirical estimate of €33-36 (Natural Resources Finland

2018c). The BLV is zero when interest rate is 1.9%[3]. This is the internal rate of return for investments in continuing timber production in the form of seedling felling and other regeneration actions.

Given 1% and 3% interest rate, the value of discounted carbon sequestration with conventional management are $p_c \times 28.6\ tCO_2ha^{-1}$ and $p_c \times 56\ tCO_2ha^{-1}$, i.e. lower than in any of the optimal solutions with or without optimized thinning (cf. Tables 1 and 2). Figure 4c shows that the carbon stored in products releases rapidly after thinning since thinning produces only pulpwood (Figure 4b). In contrast, at the seedling felling where all but the 80 seed trees are harvested, carbon remains stored in products much longer after the felling (Figure 4c). In sum, the carbon-storing properties of conventional forest management are low.

When the external cost to reindeer management is included, the decrease in NPV is €1628 and €659 with interest rates 1 and 3% respectively implying that with 3% interest rate and without the value of carbon storage, the NPV falls below zero. The BLVs are €179 and $-$€1332 given the 1% and 3% interest rates.

Value of old-growth stands

This far we have applied the common assumption in optimal rotation models that the initial forest state is the state in the beginning of the rotation period. Next, we take the initial forest state to represent an existing old growth natural forest in upper Lapland. Data for this purpose is by Multi-Source National Forest Inventory (Tomppo et al 2008, Paikkatietoikkuna 2017). We choose three sites with high density in the Inari municipality area and compute their average standing volume of commercial timber. This yields 49m^3 of saw timber, 106.3m^3 of pulpwood and 13.7m^3 of birch per hectare. Given a seedling felling according to the instructions for conventional forest management (Metsähallitus 2014), the residual stand consists 80 seed trees (pine) and 20.3m^3 of saw timber and

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3 $-1203-169-385b^{25}+1512b^{25}-581b^{80}+4275b^{105}+b^{105}\left(-169-385b^{25}+1512b^{25}-581b^{80}+4275b^{105}\right)\left(1-b^{105}\right)^{-1}=0$ $when\ b \approx 1/\left(1+0.01857\right)$.

12.5m^3 of pulpwood. Data on the size structure of existing stands is not available and the immediate value of the seedling felling is obtained applying the stumpage prices in Appendix A, Table A3. Given the initial old growth and seed trees are at a state where growth is negligible and that forest management after the seedling felling is continued as explained in Figure 4a-c we obtain the outcome shown in Table 4 and Figure 5a,b.

The seedling felling yields immediate revenues of €2213 and after this the net present values over infinite time horizon are €2554 and €251 with 1% and 3% interest rates. Thus, converting old growth to timber production yields net revenues of €4767 or €2464 depending on the rate of discount. Given these figures there is no question on whether the conversion of old growth forest land to timber production wouldn't pay off when evaluated with a pure timber NPV. However, the BLV values equal €1350 and $-€953$. The BLV is zero when interest rate equals 1.5%.[4], which represents the internal rate of return from continuing timber production after the initial felling.

Table 4: Economic consequences of conventional management applied to old growth stands.

Interest rate, %	Price of carbon, € tCO_2^{-1}	Immediate timber revenues from seedling felling, € ha^{-1}	NPV of carbon emission costs from seedling felling, € ha^{-1}	NPV of timber production after seedling felling. € ha^{-1}	NPV of carbon revenues after seedling felling. € ha^{-1}	NPV of external cost to reindeer husbandry, € ha^{-1}	Value of old-growth with/without the effects on reindeer husbandry, € ha^{-1}
3	40	2213	-5818	251	897	-659	-3116/-2415
	20	2213	-2909	251	448	-659	-656/3
	0	2213	0	251	0	-659	1805/2464
1	40	2213	-6467	2554	2095	-1628	-1233/395
	20	2213	-3234	2554	1048	-1628	953/2581
	0	2213	0	2554	0	-1628	3139/4767

Note: NPV = net present value.

The seedling felling decreases carbon storage and it takes the length of the whole rotation before the initial storage is restored as shown in Figure 5a. Depending on the interest rate and the social price of carbon, the economic cost of this decrease in carbon storage is high even net of carbon storage that

[4] $-1203-169-385b^{25}+925b^{25}-581b^{80}+4275b^{105}+b^{105}\left(-169-385b^{25}+1512b^{25}-581b^{80}+4275b^{105}\right)\left(1-b^{105}\right)^{-1}=0$ $when\ b\approx 1/\left(1+0.015\right)$.

occurs after seedling felling (Table 4). Since higher interest rate increases the relative weight of early cost of carbon emissions, increasing the interest rate increases the negative economic effect of the initial carbon release from seedling felling. Thus, high enough carbon price causes the net present value of conventional forest management to turn negative. Break-even curves in Figure 5b show the carbon price and interest rate combinations that determine whether the conversion of old growth to timber production is justified. Given a 3% interest rate but neglecting the externalities on reindeer husbandry a carbon price of €20.0 tCO_2^{-1} is enough to turn the conversion unprofitable. Including the externalities decreases the break-even price to 14€.

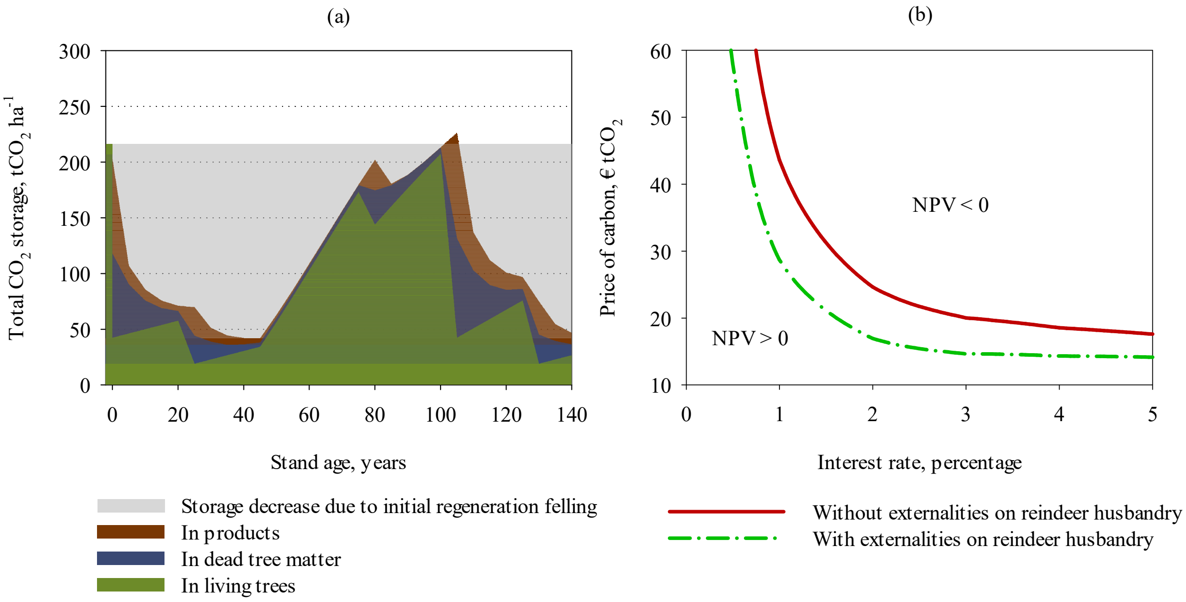

Figure 5a,b. a) Development of carbon storage in the stand and wood products when applying conventional forest management to existing old-growth forest and b) the corresponding break-even curves for the positive net present value under carbon pricing.

6 Discussion and conclusions

Table 5 collects the profitability results when timber production is viewed without carbon sequestration. The results show that seedling felling yields positive NPV. However, these profitability figures do not include the fact that the value of the seed trees maintained in seedling fellings forms a part of the regeneration cost and their value could be realized in seedling felling. Subtracting this alternative cost from the NPV yields the BLV that changes its sign between 1% and 3% interest rate. Negative bare land value implies that from the point of view of maximizing the pure net timber revenues, the optimal solution would be a clearcut without any investments on future timber production. Such solutions are sometimes called “forest mining”.

Table 5. Profitability of timber production with and without externalities on reindeer husbandry

	Without externalities				With externalities			
Solution type	NPV 1%	NPV 3%	BLV 1%	BLV 3%	NPV 1%	NPV 3%	BLV 1%	BLV 3%
No thinning	3728	631	2525	-572	2141	-39	938	-1242
Optimal thinning	5040	803	3837	-400	3844	174	2641	-1029
Conventional management	3010	530	1807	-673	1382	-129	179	-1332
Old growth and conventional management	4767	2464	1351	-952	3139	1805	-277	-1611

Note: all figures in $€ha^{-1}$, value of carbon sequestration not included.

However, Finnish forest legislation rules out forest mining by requiring that 1200 vigorous seedlings must be generated within 25 years after a clearcut or seedling felling (Forest Decree, 1308/2013). Given this restriction, the second best solution is to continue timber production instead of abandoning a stand assuming that the revenues from a clearcut or seedling felling covers the necessary regeneration costs. Given our roadside prices and harvesting cost, this condition is met. When the initial state is an old growth stand, the initial seedling felling yields €2213 and NPV remains positive independently on the rate of interest and, in particular, with the 5.6% target (and actual) rate of return of the organization in responsible on the management of public lands (Metsähallitus 2019)[5]. However, this profitability is possible only because of the initial capital that in the case of old growth typically exists without human effort. Given the target of 5.6% rate of return, harvesting the initially existing trees may be labelled as “mining of forest capital” since timber production besides the initially existing trees yields negative present value of net revenues if interest rate exceeds 1.9%.

[5] In their 2018 report, the state auditors criticized the unclear origin of the rate of return figures given by Metsähallitus (Valtiontalouden tarkastusvirasto 2018).

When the external effects of seedling felling on reindeer husbandry is included, the NPVs with 1% interest rate show positive sign but fall below zero with interest rate 3% or higher in cases without thinning (-€39) and conventional management/land with seed trees (-€129). The BLVs are negative in all cases with 3% interest rate and with 1% when the origin of seed trees is an old growth.

Finnish legislation allows negative effects on reindeer husbandry if the effects are not remarkable. The exact interpretation of this legislation has not been clarified in count but when clearcuts or seedling fellings continue for decades, the cumulative effect may become high. If the reindeer populations are not simultaneously decreased, the outcome is degradation of reindeer pastures and there is an ongoing debate whether the origin behind pasture degradation are the levels of reindeer populations or changes in land use. In their study, Sandström et al. (2016) find that in Swedish Lapland, forestry explains the degradation of reindeer pastures instead of variations in reindeer densities. As one solution, they propose CCF but without further analysis. According to our results, CCF becomes optimal even without including the externalities on reindeer husbandry if interest rate is 2-3% or higher. Including the externalities CCF becomes competitive even with 1% rate of interest. According to the data in Sandström et al. (2016), a basal area between $10-15m^2$ is optimal for lichen growth. Albeit CCF produces open pine forests that are most favorable as reindeer pastures, the solutions that aim to maximize timber revenues do not fully coincide with stand density of $10-15m^2$ suggesting that CCF should at least partly be adjusted for the purposes of reindeer husbandry. One line of criticism points out the uncertainties of natural regeneration under CCF. However, at the CCF steady state, the number of trees with diameter similar to seed trees is close to their number after the seed tree felling and increasing their number implies only minor decrease in CCF net revenues. This increase in large diameter trees may contribute to both natural regeneration as well as the amount of ground and arboreal lichen.

An influential paper by Fargione et al (2008) has created a large literature to study the conversion of natural forests to plantations and the associated changes in CO_2 storage and emissions.

Central concepts in these studies are "carbon debt" and "payback period". The former refers to the fact that clearcutting a natural forest yields an initial rapid release of CO_2 into the atmosphere that is repaid during the payback period by production of biofuels and resulting hypothetical substitution of fossil fuels. A large number of studies have computed estimates for the payback times and e.g. in Malcolm et al (2020) the payback time for Canadian boreal forest may vary between 93-757 years depending for example on the assumptions of the substituted type of fossil fuel. A long payback period is taken to expose that old growth forest should be saved from land conversion to timber production (Malcolm et al. 2020). This line of research has its merit in questioning the "carbon neutrality" of forestry but as such, the computation of the payback period is not based on any generic economic approach on the potential of forest resources in climate change mitigation. In particular, it does not include economic analysis of the tradeoffs between the value of timber production and carbon sequestration, it describes timber production in converted land without economic optimization and circumvents interest rate and intertemporal economic analysis. We additionally remark the sharp contrast with the setup in Martin et al. (2017) and Ruppert et al. (2016) where the present industrial demand of timber is taken as fixed in integrating forestry and maintaining woodland caribou habitats.

We apply an economic approach and integrate wood production, carbon sequestration and the value forests as reindeer pastures. This leads to a different point of view in analyzing the conversion of old growth forest to timber production. One crucial difference is that our setup, instead of assuming a hypothetical substitution of bioenergy for fossil fuels, applies actual data on industrial use of harvested wood in Finland. Including carbon sequestration and social price of carbon into the objective together with timber net revenues increases the NPV and BLV, changes harvests but decreases the NPV from timber production (Tables 1 and 2). The grey areas in Figure 5a and Figures 6a-f show the difference of carbon stock in an initial old growth forest and carbon pools in standing biomass, deadwood and wood products after the land conversion. Albeit the initial storage level is occasionally reached, on average the level of carbon storage remains below level of the old growth, i.e. the payback period is infinitely long. In spite of this, with carbon prices of €20 tCO_2^{-1} and €40 tCO_2^{-1}, the land conversion to optimal joint production of timber and carbon sequestration becomes economically justified.

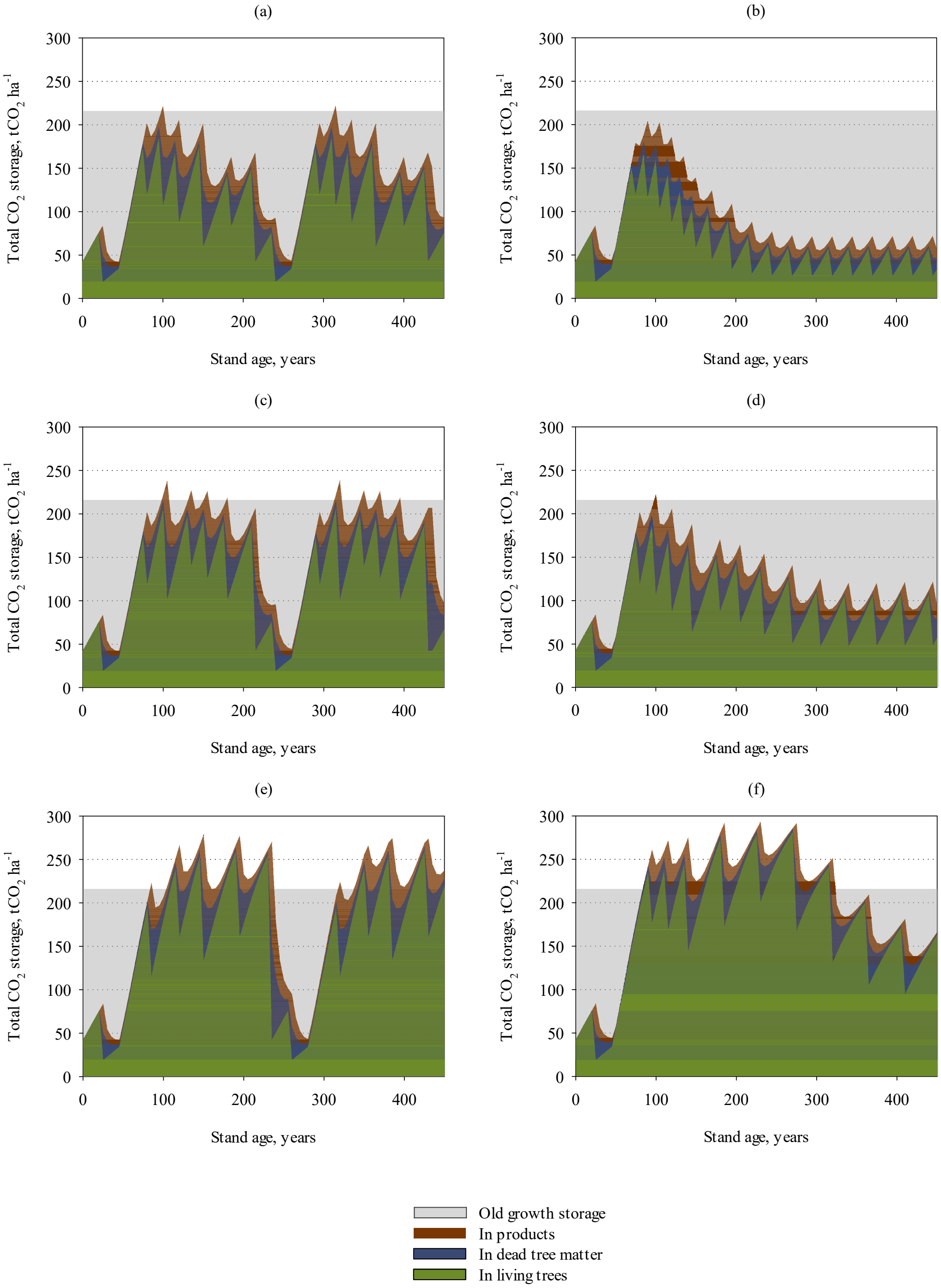

Figure 6 a-f. Carbon storage development in the optimal solutions with 1% interest rate and €0 tCO_2^{-1} (a), €20 tCO_2^{-1} (c) and €40 tCO_2^{-1} (e) carbon prices and with 3% interest rate and €0 tCO_2^{-1} (b), €20 tCO_2^{-1} (d) and €40 tCO_2^{-1} (f) carbon prices.

Table 6. Cost and choke price of carbon sequestration $€tCO_2^{-1}$

	No thinning		Optimal thinning		Conventional management		Conventional management, old growth	
Interest rate	1%	3%	1%	3%	1%	3%	1%	3%
Cost with carbon price $20€tCO_2^{-1}$	9.6	12.4	8.0	19.0	-	-	-	-
Cost with carbon price $40€tCO_2^{-1}$	22.8	21.8	20.7	27.7	-	-	-	-
Choke price of carbon	60/55*	40/35*	100/100*	60/60*	77/60*	49/42*	44/29*	20/14*

Note: *=with externalities to reindeer husbandry

Table 7 shows that with carbon prices of €20 – €40 the cost per ton of CO_2 sequestrated varies between €8 and €27.7. As shown numerically in van Kooten et al. (1995) and analytically in Tahvonen and Rautiainen (2017), a high enough carbon implies (without optimized thinning) that rotation period approaches infinity and it becomes optimal to use forests as a carbon storage only. Given the setup of Upper Lapland these choke prices are €60 and €40 when optimized thinning is excluded and decrease €5 after including the externalities on reindeer husbandry. Optimized thinning increases the choke prices to €100 and €60 depending on the rate of interest.

The choke prices are lower when the initial state is an old growth forest because the net revenues from the seedling felling are lower compared to the case where the stand in seedling felling is a managed forest. Additionally, conventional management do not react to carbon sequestration and choke prices decrease compared to prices based on optimization. Thus, with 3% rate of interest the choke prices are €20 or €14 depending externalities to reindeer husbandry. We note that the choke price results do not have any clear connections with the payback period or carbon debt.

If the interest rate is 3%, externalities on reindeer husbandry are included and the carbon price is between €14 and €42, it is preferable not to convert an old growth forest to timber production albeit if a stand is already in timber production, continuing forestry is preferable. Similar results can be obtained when timber production is optimized instead of conventional management. This is an example where the initial stand state may have qualitative implications on optimal long-term management choices (cf. Strand 1983 and Tahvonen 2015).

We remark that our results could change if the timber supply from Upper Lapland public lands influences timber prices. Historically, the total annual harvested timber in Upper Lapland has been around 0.24 million cubic meters of which less than 50% is from public lands. This is only a small fraction of the 4.33 million cubic meters annually harvested in the whole Lapland timber supply region (Keskimölö and Väisänen 2012). Thus, the effect of timber supply changes in Upper Lapland public lands on timber prices should be minor.

Estimates on social price and actual tax rates of carbon vary widely and European Commission (2014, p. 80) has projected the EU ETS price to equal €85–€264 tCO_2^{-1} in 2050. The choke price of €14 obtained by including the externalities on reindeer husbandry and assuming 3% interest rate is low compared to these projections and compared to the EU emission trading price per tCO_2 that has been above €14 since May 2018. As an EU member state Finland must cope with the LULUCF regulation that restricts net emissions from land use including forestry. Given that these requirements became binding, their fulfilment by maintain the old growth forest in upper Lapland as carbon storage and reindeer pastures may well be among the socially preferable cost efficient alternatives.

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Appendix A

Table A1: Size class specific parameter values for Scots pine.

Size classes	γ_s	d_s	v_{1s}	v_{2s}
1	0.0044	75	0.01511	0
2	0.0123	125	0.07120	0
3	0.0241	175	0.14876	0.02851
4	0.0398	225	0.13498	0.19973
5	0.0594	275	0.19151	0.34294
6	0.0830	325	0.37497	0.39755
7	0.1106	375	0.55767	0.46149

Note: γ_s, $s=1,...,7$ is the basal area of a tree (m^2), $d_s, s=1,...,7$ is the diameter breast height (midpoint) of the size class (mm), v_{1s}, $s=1,...,7$ and v_{2s}, $s=1,...,7$ are the pulpwood and sawlog volumes (m^3) per tree, respectively. The volumes correspond to volumes in Motti stand simulator.

Table A2: Scots pine timber prices in euros per m^3.

	Scots pine, roadside price	Scots pine, stumpage price	Birch, stumpage price
Sawlog	51.0	38.0	18.7
Pulpwood	26.2	12.2	18.7

Note: Prices based on Metsänhoitoyhdistys Ylä-Lappi (2017), Natural Resources Institute Finland (2018).

Table A3: Parameter values for the harvesting cost function.

i	C_{i0}	C_{i1}	C_{i2}	C_{i3}	C_{i4}	C_{i5}	C_{i6}	C_{i7}
th	2.100	1.150	0.547	0.196	-0.308	1.000	2.272	0.535
sf	2.100	1.000	0.532	0.196	-0.308	1.000	1.376	0.393

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Corso Magenta 63, Milano – Italia

Tel. +39 02.520.36934
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