Economics of boreal Scots pine stands under changing climate

Corresponding author: Sampo Pihlainen, Department of Forest Sciences, University of Helsinki, P.O. Box 27, FI-00014 Helsinki, Finland. E-mail: sampo.pihlainen@helsinki.fi, Tel: +358919157990, Fax: +358919158100.

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

Annikki Mäkelä, Department of Forest Sciences, University of Helsinki, P.O. Box 27, FI-00014 Helsinki, Finland. E-mail: annikki.makela@helsinki.fi

Abstract

We optimize the joint production of timber and carbon storage of Scots pine (*Pinus sylvestris* L.) stands in a changing climate. In our economic-ecological model, a detailed process-based forest growth model is combined with economic description of stand management. Optimization is carried out with an effective general pattern search algorithm. The growth model includes a direct link between climate change and tree growth. In the course of climate change, the rotation periods must be allowed to change. Consequently, the optimization problem becomes complex. The optimized variables for each rotation in the changing climate are the timing, type, intensity and number of harvests, as well as the initial stand density. The results are presented for all relevant Nordic sites and using various levels of carbon subsidy. Our results suggest that the optimal rotation length decreases with changing climate, if thinnings are not allowed. With optimal thinnings the optimal forest rotations first lengthen and then shorten, thinnings become heavier and the optimal number of thinnings increase. Timber production and carbon storage both increase remarkably with climate change, especially at poor sites. Optimally adapted stand management yields significantly higher bare land values compared to benchmark management.

Keywords: carbon storage**,** climate change, forest economics, generalized pattern search, optimal initial density, optimal rotation, optimal thinning, process-based growth model, Scots pine, value of adaptation, optimal adaptation

1 Introduction

Forests have an outstanding role in the mitigation of climate change (IPCC 2014). As climate change poses an immense challenge to mankind, it is of utmost importance to fully utilize the forests' potential in the mitigation via carbon storage and timber production. To achieve this, current forest management decisions should anticipate the future growth conditions for a long time horizon. Scots pine (*Pinus sylvestris* L.) is one of the most abundant tree species in the world and its significance in boreal region is proposed to increase with climate change because of its heat tolerance (Lutz et al. 2013). Therefore, determining optimal stand management of Scots pine in changing climate is crucial. This study presents novel results on economically optimal adaptation when timber production and carbon storage are integrated using a detailed ecological-economic model.

Climate change is predicted to be particularly significant in the boreal region, where average temperature is forecasted to increase more than it increases in the world on average (IPCC 2014). As in Fennoscandia soil water is not a limiting factor but the short growing season and low temperature are (Kellomäki et al. 1997b), forest growth is anticipated to increase with increasing temperatures (Pussinen et al. 2002), with the increase being higher in northern areas (Matala et al. 2006). While the carbon storage in vegetation is suggested to increase, the overall forest carbon stock is proposed to decrease because of the decrease in the soil carbon stock (Mäkipää et al. 1999).

The impact of climate change on timber production and carbon storage is usually studied assuming no adaptation in forest management. However, the potential of adaptation in forest management may be remarkable. An example of this is highlighted in Sohngen and Mendelsohn (1998), who study the impact of climate change on the United States timber markets using a dynamic analysis in order to capture the intertemporal adaptation. Their nation-wide timber market model solves periodically the equilibrium prices, the harvests and the choice of regenerated species, and determines the price path that leads to the new steady state. As a result they find that the dynamic market adjustments dampen the effects of harmful changes in ecosystems.

Forest management adaptation strategies to changing climate are diverse. According to the influential paper by Millar et al. (2007), adaptive strategies can be divided in three categories: resistance, resilience and response options. The first category denotes improving the forest defenses against direct and indirect effects of environmental changes, considering mostly fires, insects and diseases. The second category denotes improving the forest ability to recover from disturbances. Our study falls into the third category, which includes adaptation options facilitating the transitions of forest ecosystems to new environmental conditions. We focus on the optimization of harvest schedules, thinning prescriptions and the initial stand density in changing climate but do not study the question of species selection. This differentiates our study from the studies focusing on selecting the most suitable tree species for changing conditions (see for example Hanewinkel et al. 2010, 2012). Guo and Costello (2013) call these two approaches in this category “adaptation on the intensive margin” and “adaptation on the extensive margin”, respectively. We note that before the adaptation in the sense of selecting the most suitable species can be made one must first know the full economic potential of each tree species in changing climate.

The most common approach for studying the adaptation of harvest schedules and thinning prescriptions to changing climatic conditions is to compare different management scenarios. Using this approach under Nordic conditions, Garcia-Gonzalo et al. (2007b) find the changing climate to give the highest increase to the timber yield, when the initial age class distribution of tree stands in a forest landscape is normally distributed. Garcia-Gonzalo et al. (2008) combine a model for wood products with a multi-objective regional optimization (with fixed thinning strategies), and find that the preferable regional management plans in the changing climate include mostly stand treatments that hold a higher stocking and postponed harvests compared to the currently recommended treatments. Nuutinen et al. (2006) use a regional forestry model and maximize sustained timber yield (MSY) for a mixed-species forest using six scenarios with differences in climate and forest management. They find that the MSY and the significance of thinnings increase with changing climate. When comparing the management scenarios for pure Scots pine stands in Finland, Briceño-Elizondo et al. (2006a) find the timber yield to increase, Briceño-Elizondo et al. (2006b) the carbon stock to increase, Kellomäki et al. (1997a) the rotation period to shorten, and Kellomäki and Kolström (1993) the thinnings and clearcut to be performed earlier.

All the aforementioned studies offer only a partial analysis on the economics of forest management in changing climate since they fall short of simultaneous optimization of forest management actions and do not evaluate various scenarios by any objective function integrating both timber production and carbon storage. These studies commonly use only a 100-year-phase of gradual climate transition as the planning horizon, thus focusing only on one rotation. Moreover, the choice of silvicultural solutions to be analyzed is commonly guided by MSY-type objective and solutions that provide less timber than would be obtainable in current conditions without climate change are excluded. Such exclusions are not justifiable in economic analysis, where the economic optimum is not directly determined by the level of timber yield.

Optimization of harvest schedules and prescriptions in changing climate is a challenging task. Optimal rotation periods and other decision variables may change in the course of time with changing growth conditions. Goetz et al. (2013) study uneven-aged Scots pine stands in Spain with a fixed harvesting and planting period and find that the optimal number of trees increases with changing climate. Pukkala and Kellomäki (2012) maximize the present value of net revenues from timber production in mixed-species even-aged stands by optimizing the rotation length as well as the timing and the intensities of two thinnings. However, in their analysis all rotations are equal, an assumption that is clearly restrictive in changing climate. They find the harvests to be performed earlier in changing climate compared to current climate with no climate change. Löfgren (1985) analytically determines the optimal rotation with a model where the forest growth changes as a result of biotechnological improvements. However, in his model the growth potential stays the same during a rotation. The rotation is usually shorter with improving growth, but the effect depends on the development of growth in the future. McConnell et al. (1983) approach a similar problem with a model where timber prices and costs evolve over time, finding that the change in optimal rotation depends on the development of prices and costs. In these analytical models the only choice variable is the rotation length.

As far as we know, this is the first study to optimize even-aged forest stand management where successive rotations are allowed to change with changing climate. Furthermore, this is the first study to include carbon storage objective in economic optimization of even-aged forest management under changing climate. We provide a complete picture of optimal timber production and carbon storage at Scots pine (*Pinus sylvestris* L.) stands in all relevant Nordic growth conditions. We follow the interdisciplinary stand-level optimization tradition established in Haight et al. (1985) and Getz and Haight (1989) where stand growth is described by detailed ecological models, optimized variables include initial stand density and thinning in addition to rotation length and the optimal solution is found by numerical methods. We apply a highly-detailed process-based growth model, where climate change affects several factors determining annual tree growth. Optimization is performed over an infinite horizon and the stand management of successive rotations in changing climate is allowed to change. The optimized variables for each rotation in the changing and the changed climate are the timing, type, intensity and number of harvests, as well as the initial stand density. The economic details include differentiated prices for five different timber grades and various levels of carbon subsidy. Carbon pool includes the carbon in merchantable timber and in decaying timber products. Value of adaptation to climate change is determined by comparing the maximized bare land value assuming climate change to the one obtained by continuing the presently optimal solution (with no climate change) under the conditions of predicted climate change.

2 Model and methods

Our stand-level optimization problem is based on an individual-tree process-based growth model developed in Mäkelä (1997), Mäkelä (2002), and Mäkelä and Mäkinen (2003) and parameterized for pure Scots pine stands. The model is integrated with economic optimization in Hyytiäinen et al. (2004) and Tahvonen et al. (2013) and extended to include carbon subsidy systems in Pihlainen et al. (2014).

The stand structure in the model is defined by n tree classes or subject trees. The trees in a given tree class are identical. Interaction with other trees influences photosynthesis, growth and natural mortality. The model can be described as a dynamic system depicting the development of state variables over time. The number of state variables m is $n+nu+nyg+nlsg$, where n is the number of stand-level variables (denoting the number of trees in each tree class), u the number of tree-level variables (denoting for example the masses of different tree compartments), y the number of whorl-level variables for g whorls, and l the number of branch-level variables for s branches in each whorl. In the current version of the model, $n=10$, $u=11$, $g=60-140$, $y=3$, $s=5$ and $l=2$, implicating that the number of state variables varies between 7921 and 18 321, when including also stand age t.

Let $z_{ij,t+1}$ denote the value of the state variable j of trees in tree class i at the beginning of the year $t+1$. It is determined in the process-based model as a function of all state variables and a possible harvest at the year t.

$$(1) \quad z_{ij,t+1} = f\left(z_{11t},...,z_{1mt},z_{21t},...,z_{2mt},...,z_{n1t},...,z_{nmt},\gamma_{1t},\gamma_{2t},\gamma_{3t}\right), \quad i=1,\dots,n,\ j=1,\dots,m,$$

$$(2) \quad \frac{h_{it}}{z_{i1t}} = \gamma_{1t},\ i=1,2,3,\ \frac{h_{it}}{z_{i1t}} = \gamma_{2t},\ i=4,5,6,7,\ \frac{h_{it}}{z_{i1t}} = \gamma_{3t},\ i=8,9,10,\ t= 0,\dots,t_k,$$

where γ_{dt_s} denotes thinning intensities which are optimized separately for dominant trees ($d=1$), co-dominant trees ($d=2$), and suppressed trees ($d=3$) for each harvest at stand age t_s, $s=1,\dots,k$, $h_{it}, t=0,...,t_k$ denotes the number of harvested trees in each tree class, and $z_{i1t}, t=0,...,t_k$ the number of trees in each tree class. Furthermore, the initial values of state variables z_{ij0}, $i=1,...,n$, $j=1,...,m$ are given, except the number of seedlings, N_0, which is an optimized variable.

The change in climate is simulated in the process-based growth model following Bergström et al. (2011). The change corresponds to 4.5°C increase in (Nordic) temperature in the next hundred years compared to the average temperature in the period 1971–2000 (Figure 1a). Furthermore, the CO_2 emissions from fossil fuel combustion are assumed to increase by 100% by the year 2050 and slightly decrease after that. This causes the CO_2 content of the atmosphere to increase from 380 ppm to 700 ppm. These assumptions correspond to scenario A1B in Jylhä et al. (2009), denoting “rather large emissions”, which cause a “moderate climate change”.

The growth model in this study includes a direct link between the climate change and tree growth. Tree growth is influenced by increased temperature and elevated CO_2 level in atmosphere, as well as enhanced nutrient turnover in the soil organic matter, and the effects of drought. Corollary to this, the level of total rate of photosynthesis of a stand, maintenance respiration of trees and the biomass allocation to roots are multiplied in the growth model by coefficients. The values of the coefficients for total rate of stand photosynthesis and maintenance respiration of trees increase and for biomass allocation to roots decrease somewhat linearly for the first 100 years and stabilize after that (Figure 1b).

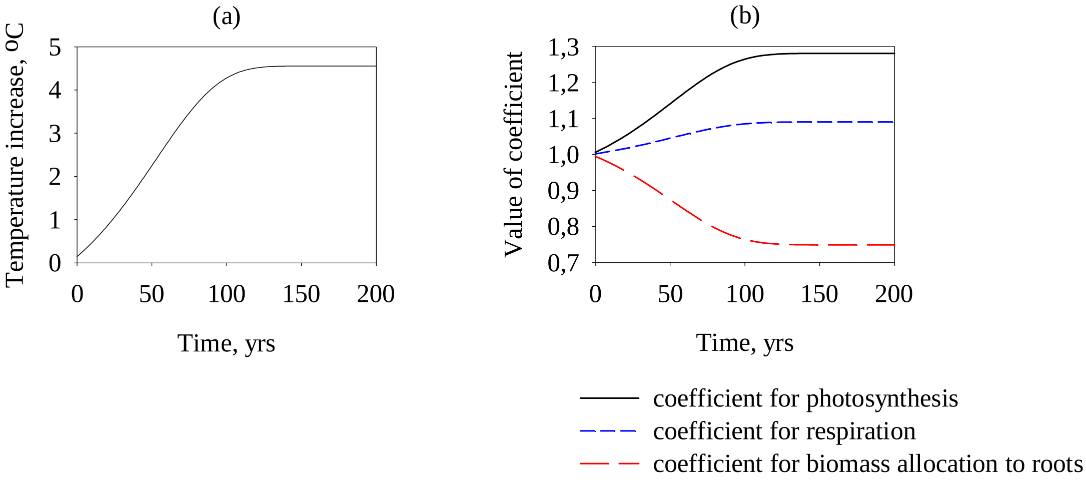

Figure 1. The development over time of (a) temperature in Fennoscandia and (b) climate change coefficients multiplying the benchmark level of total rate of photosynthesis at stand, the respiration of trees and the biomass allocation to roots.

We first compute the maximized bare land value solution given the stabilized climate. The optimized variables are the number of seedlings N_0, the number k, the timing t_s, $s = 1, \ldots, k$ and the intensity γ_{dt_s}, $d = 1, 2, 3$ of the harvests. This optimization problem can be given as:

$$(3) \quad \max_{\left\{ \begin{smallmatrix} N_0, k, t_s, \gamma_{dt_s}, \\ d=1,2,3, s=1,\ldots,k \end{smallmatrix} \right\}} J_\infty = \left\{ \frac{\sum_{s=1}^{k} b^{t_s} \left\{ \sum_{i=1}^{n} \sum_{v=1}^{g} p_v D_{ivt_s} h_{it_s} - C\left(\mathbf{h}_{t_s}, \mathbf{D}_{t_s}\right) \right\} + \sum_{t=0}^{t_k} b^t p_c Q_t - w}{1 - b^{t_k}} - \frac{A}{r} \right\} (1 - \rho),$$

subject to (1), (2) and nonnegativity conditions for the control and state variables.

The gross revenues from harvest $s = 1, \ldots, k$ are determined for tree class $i = 1, \ldots, \mathrm{n}$ by multiplying timber assortment ($v = 1, \ldots, g$) specific price p_v with the corresponding volume D_{ivt_s} and number of harvested trees h_{it_s}. Details on bucking, prices, harvesting cost $C\left(\mathbf{h}_{t_s}, \mathbf{D}_{t_s}\right)$, administration cost A, rate of capital taxation ρ, and stand establishment cost w, are given in Appendix A and Tahvonen et al. (2013). The parameter p_c denotes the market price of carbon (in € tCO_2^{-1}), and $b = 1/(1+r)$ is the discount factor where r is the interest rate, which in this study is assumed to be 3%.

The objective function includes the variable Q_t, which denotes the change in the carbon pool (in tCO_2) during the year t. It is defined as

$$(4) \quad Q_t = \mu \sum_{i=1}^{n} \left\{ \left(q_{it} z_{i1t} - q_{i,t-1} z_{i1,t-1} \right) + \sum_{\phi=1}^{2} \left\{ \left[1 - \beta_\phi (r) \right] x_{i\phi t} h_{it} \right\} \right\},$$

where q_{it} denotes the merchantable timber volume of each subject tree in the end of year t. Dead trees are assumed to release their carbon immediately. However, carbon in harvested trees ends up in products, where it decays according to the production-line-specific rate. The variable h_{it} is the number of trees harvested at year $t = 0, \ldots, t_k$ from each tree class $i = 1, \ldots, \mathrm{n}$ and $x_{i\phi t}$ is the volume of each harvested tree going either to a sawmill $(\phi = 1)$ or to chemical pulp and paper $(\phi = 2)$. The parameter $\beta_\phi(r)$ is the present value of volume lost in decay, and using a 3% interest rate $\beta_1(0.03) = 0.4413$ and $\beta_2(0.03) = 0.9207$. The physical decay estimates are obtained from Liski et al. (2001).

The parameter μ converts the wood and product volume (in m^3) into corresponding carbon dioxide mass (in tCO_2) and is defined as $\mu = \sigma\chi\theta$, where $\sigma = 0.40\,(t\,m^{-3})$ is the wood density of Scots pine (Mäkelä 2002), $\chi = 0.5$ is the carbon fraction of the mass of dry wood (Penman et al. 2003), and $\theta = 3.67$ is the factor depicting the mass increase in the conversion from carbon (C) into carbon dioxide (CO_2).

The period of changing climate is 100 years and it contains enough rotations to reach the stabilized climate. In this paper, the number of rotations needed to reach the stabilized climate is assumed to be three maximum. The optimized variables in the three rotations in changing climate are the number of seedlings N_{0a} and the number k_a, the timing $t_{s_a}, s_a = 1,...,k_a$, and the intensity $\gamma_{dt_{s_a}}, s_a = 1,...,k_a,\ d = 1,2,3$ of harvests, when $a = 1,2,3$ denotes the ordinal of the rotation. The overall objective function is:

$$(5)\quad \max_{\left\{\begin{array}{l} N_{0_a}, k_a, t_{s_a}, \\ \gamma_{dt_{s_a}},\ d=1,2,3, \\ s_a=1,...,k_a, \\ a=1,2,3 \end{array}\right\}} J = \left(W_1 + b^{t_{k_1}} W_2 + b^{t_{k_1}+t_{k_2}} W_3 - \frac{A}{r}\right)(1-\rho) + b^{t_{k_1}+t_{k_2}+t_{k_3}} \left(J_\infty + (1-\rho)\frac{A}{r}\right),$$

$$\text{where } W_a = \sum_{s_a=1}^{k_a} b^{t_{s_a}} \left[\sum_{i=1}^{n}\sum_{v=1}^{g} p_v D_{ivt_{s_a}} h_{it_{s_a}} - C\left(\mathbf{h}_{t_{s_a}}, \mathbf{D}_{t_{s_a}}\right)\right] + \sum_{t=0}^{t_{k_a}} b^t p_c Q_t - w,\ a = 1,2,3,$$

subject to (1), (2) and nonnegativity conditions for the control and state variables.

Optimal solutions are computed separately for (fertile) *Myrtillus*- (MT), (average fertily) *Vaccinium*- (VT), and (infertile) *Calluna*-type (CT) (Cajander 1949) sites growing in Southern Finland (temperature sum 1300 dd (Ruosteenoja 2011)) and for *Myrtillus*-, and *Vaccinium*-type sites in Central

Finland (temperature sum 1100 dd (Ruosteenoja 2011)). We abbreviate these sites as: MT1300, VT1300, CT1300, MT1100 and VT1100, respectively. The optimal initial density was chosen from the discrete set of [1500, 2000, 3000] seedlings per hectare. This density refers to the state of the stand after tending. Thus, the initial state of the stands consists of trees of 20-29 years, depending on site. The initial state of stand at a particular site and in a particular density is the same irrespective of the climatic specification.

A general pattern search algorithm (Kolda et al. 2003, The MathWorks, Inc 2013) was used in the optimizations. Solving the optimization problem is complicated by non-convexities and the global optimum candidate solutions are based on 100 initial guesses.

3 Results

The impact of climate change on optimal forest management without carbon storage objective

When thinning is not allowed, optimal rotations tend to shorten with changing climate (Table 1). Given all five site types, the optimal length of the first rotation in the changing climate is on average 4 years shorter than the length of the rotation in the current climate with no climate change (hereafter denoted as current climate). Furthermore, the second rotation in the changing climate is on average 2 years shorter than the first. The rotation length in the changed climate is on average 7 years shorter compared to the optimal rotation based on the current climate. The optimal number of seedlings is 1500 at all sites and dates.

Adding optimized thinning to the framework changes the picture considerably. Optimal rotation tends to first lengthen with changing climate and then shorten (Table 2). The impact of climate change on decision variables depends heavily on stand type (columns 3-5 from left in Table 2). At good sites (MT1300, VT1300, MT1100) the optimal length of the first rotation in the changing climate is on average 16 years longer than the length in current climate. This is because the optimal number of thinnings simultaneously increases, on average by two thinnings. However, in the second rotation in the changing climate, the number thinnings tend to stay the same, resulting on average in 9 years shorter rotation. The differences between the optimal lengths of the second rotation in the changing climate and the rotation in the changed climate are minor. The optimal rotation in the changed climate is on average 8 years longer than in current climate.

At poor sites (VT1100, CT1300) the impact of climate change on decision variables is stronger than at good sites. The optimal length of the first rotation in the changing climate is on average 37 years longer than the one in the current climate and the number of thinnings increases by three on average. Because at poor sites the first rotation in changing climate already reaches the phase of stabilized climate ($t_{k_1} \geq 100$) there is only one rotation in changing climate. The optimal rotation in the changed climate is 19 years longer at VT1100 but 7 years shorter at CT1300, compared to the ones in the current climate.

Table 1. Optimal rotations without thinnings in different site types and climate specifications. Interest rate 3%.

Climate specification	Current[a]	Changing			Changed
		1st rotation	2nd rotation	3rd rotation	
MT1300	40	37	38	37	36
VT1300	47	46	40	40	39
MT1100	49	46	44	44	41
VT1100	55	53	49	-[b]	47
CT1300	61	52	51	-[b]	54

[a] Current climate and no climate change.

[b] Third rotation is not needed, since the first two already reach the phase of stabilized climate.

Table 2. Optimal solutions in different site types and climate specifications at various carbon prices. Interest rate 3%.

		p_c														
		0			20			40			60			100		
	Climate specification	N_0	k	t_k	N_0	k	t_k	N_0	k	t_k	N_0	k	t_k	N_0	k	t_k
MT1300	Current[a]	2000	2	77	3000	4	98	3000	4	100	3000	5	104	3000	5	133
	Changing1	2000	3	82	3000	5	86	3000	5	86	3000	5	120	3000	5	120
	Changing2	2000	4	85	3000	5	85	3000	5	85	-[b]	-	-	-	-	-
	Changed	2000	4	85	3000	5	85	3000	5	85	3000	5	85	3000	5	122
VT1300	Current[a]	2000	2	77	2000	3	86	3000	4	115	3000	4	119	3000	5	148
	Changing1	2000	4	94	3000	4	93	3000	5	110	3000	5	116	3000	5	131
	Changing2	2000	4	90	3000	4	87	-[b]	-	-	-	-	-	-	-	-
	Changed	2000	5	92	3000	4	87	3000	5	91	3000	5	91	3000	5	127
MT1100	Current[a]	1500	1	70	3000	3	93	3000	5	127	3000	5	130	3000	5	147
	Changing1	1500	3	97	3000	4	95	3000	5	100	3000	5	113	3000	5	137
	Changing2	1500	3	71	3000	5	95	-[b]	-	-	-	-	-	-	-	-
	Changed	1500	3	71	3000	5	95	3000	5	95	3000	5	95	3000	5	128
VT100	Current[a]	1500	0	55	1500	2	104	1500	4	138	3000	5	149	3000	5	149
	Changing1	1500	3	104	1500	4	109	1500	5	115	1500	4	115	3000	5	143
	Changing2	-[b]	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Changed	1500	3	74	1500	4	108	3000	5	102	3000	5	107	3000	5	119
CT1300	Current[a]	1500	1	83	1500	2	108	3000	3	119	3000	4	149	3000	5	149
	Changing1	1500	3	107	1500	4	115	1500	4	115	3000	5	128	3000	5	144
	Changing2	-[b]	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Changed	1500	3	76	3000	5	105	3000	5	105	3000	5	113	3000	5	119

[a] Current climate and no climate change.

[b] Second rotation is not needed, since the first already reaches the phase of stabilized climate.

Note: N_0 denotes initial density, k number of thinnings, t_k rotation length, and p_c CO_2 price.

The impact of climate change on optimal forest management with carbon storage objective

Note first that without climate change and with increasing carbon price the optimal rotation lengthens, the optimal number of thinnings increases, and the optimal initial density increases (Table 2). At carbon price 20 € tCO_2^{-1} the optimal length of the first rotation in the changing climate is 2-7 years longer than the one in current climate (depending on site type, Table 2). The lengthening of the rotation is again because of the increase in the optimal number of thinnings. Notwithstanding, at the site MT1300, the optimal rotation at carbon price 20 € tCO_2^{-1} is shorter in the changing climate than in the current climate. This is because the optimal number of thinnings is already high in current climate, and further increase only has a small effect on the rotation length.

At higher carbon prices, the optimal rotation length decreases with changing climate somewhat across the board (Table 2). Given all site types, the first rotation in changing climate is on average 12 years shorter than the one in current climate at carbon price 40 € tCO_2^{-1}, 10 years at 60 € tCO_2^{-1} and 9 years at 100 € tCO_2^{-1}. Comparing the two steady states, the optimal rotation in current climate is on average 20 years longer than in changed climate at carbon price 40 € tCO_2^{-1}, 27 years at 60 € tCO_2^{-1} and 19 years at 100 € tCO_2^{-1}. The main difference to the case of lower carbon prices is that here the optimal number of thinnings is already (nearly) at maximum, which is assumed to be five in this study. Therefore the lengthening of the optimal rotation due to the increase in the number of thinnings does not materialize.

Given any carbon price or site type, the optimal initial density is usually independent of climate change (Table 2). However, at poor sites at low carbon prices the optimal initial density doubles from 1500 to 3000 seedlings, when the climate changes.

The volume of standing merchantable timber is remarkably higher in the changing and the changed climate compared to the current climate (Figure 2). Given the average fertility site VT1300, the volume of standing merchantable timber at the clearcut is 61% higher in changed climate than in current climate at zero carbon price (Figure 2a), 70% higher at carbon price 20 € tCO_2^{-1} (Figure 2b) and 43% higher at carbon price 100 € tCO_2^{-1} (Figure 2c). The relative increase in the latter is smaller because at that carbon price the optimal rotation shortens with changing climate (Table 2).

The intensity of the optimal thinnings changes with changing climate (Figure 2). At the average fertility site VT1300, current climate, and carbon price of 100 € tCO_2^{-1}, the largest thinning removal is in the last thinning, amounting 147 m^3 (Figure 2c). This is considerably smaller than the largest thinning removal in the changed climate, 235 m^3. Even with increased removal in thinnings, the standing merchantable timber volume increases towards the clearcut in the changing climate.

Optimal thinnings are also carried out earlier than in the absence of climate change. Given the carbon price of 100 € tCO_2^{-1} and the average fertility site VT1300, the thinnings are at stand ages 32, 47, 63, 82 and 109 without climate change and 27, 37, 48, 66 and 89 in the changed climate (Figure 2c). At all sites, climatic specifications and carbon prices, the thinnings tend to be from above. However, the first thinning is from below if and only if the optimal initial density is high (3000 seedlings). This is to salvage trees that would otherwise be lost through natural mortality.

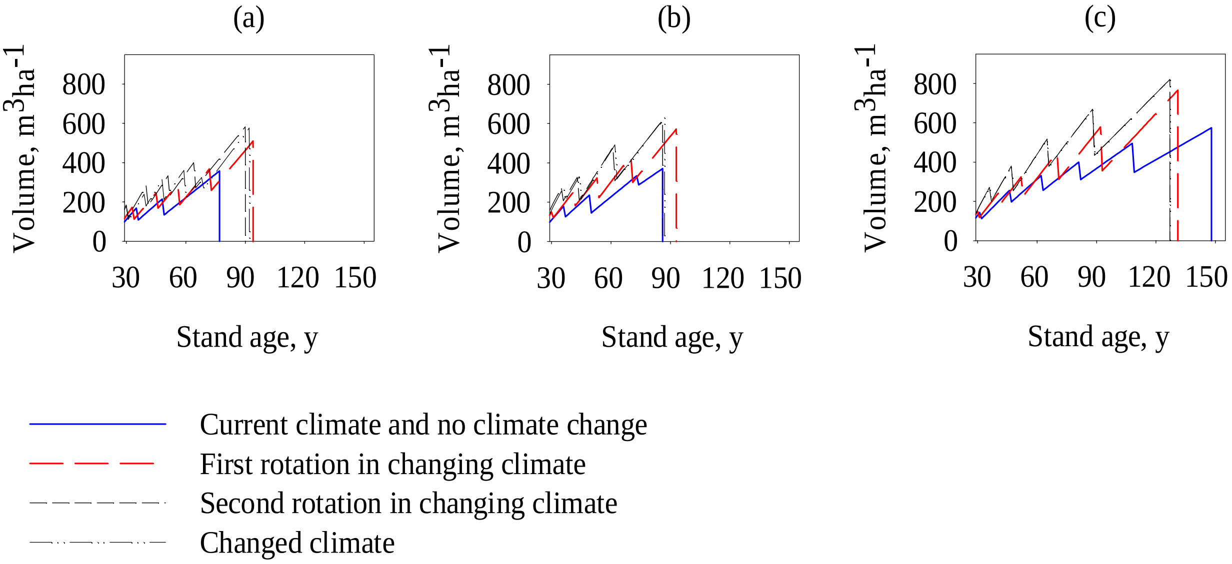

Figure 2. The development of merchantable timber volume in optimal solutions at carbon price per ton of CO_2 being (a) €0, (b) €20, (c) €100.
Site type VT1300, interest rate 3%.

The impact of changing climate on timber yield and carbon storage

The average annual timber yield increases dramatically with climate change (Table 3). At good sites (MT1300, VT1300 and MT1100) at zero carbon price the yield from first rotation in changing climate is on average 37% higher than in current climate. The increase is greater at poor sites (VT1100 and CT1300), where the corresponding increase is on average 106%. Comparing the two steady states, at good sites (poor sites) the average annual yield in changed climate is on average 60% (143%) higher than with no climate change.

With carbon subsidies, the impact of climate change on the average annual yield is lower (Table 3) than without subsidies. At good sites, the yield in the first rotation in changing climate is on average 34-39% higher than without climate change, depending on the carbon price. At poor sites the corresponding figure is 87-94%. In changed climate the yield at good sites (poor sites) is on average 53-58% (124-135%) higher than with no climate change.

The average CO_2 storage at stand increases with changing climate (Table 3). The increase at zero carbon price is again higher at poor sites (VT1100 and CT1300), where the carbon storage in the first rotation in changing climate is on average 115% higher than with no climate change. This is remarkably greater increase than the corresponding one (35%) at good sites (MT1300, VT1300, MT1100). Furthermore, the carbon storage in changed climate is at poor sites (good sites) on average 80% (38%) higher than with no climate change.

Climate change impact on average carbon storage at stand is lower with positive carbon prices compared to zero carbon price (Table 3). At the carbon price of 20 € tCO_2^{-1} the carbon storage in the first rotation of changing climate is at good sites (poor sites) on average 17% (49%) higher than with no climate change. Moreover, the storage in changed climate is at good sites (poor sites) on average 33% (72%) higher than with no climate change. The corresponding figures are even lower at higher prices of carbon.

Table 3. Timber yield and carbon storage in optimal solutions in different site types and climate specifications at various carbon prices.
Interest rate 3%.

		p_c							
		0		20		60		100	
	Climate specification	Yield[b] m^3a^{-1}	Average storage[c], tCO_2	Yield[b] m^3a^{-1}	Average storage[c], tCO_2	Yield[b] m^3a^{-1}	Average storage[c], tCO_2	Yield[b] m^3a^{-1}	Average storage[c], tCO_2
MT1300	Current[a]	7.9	152	8.8	210	8.9	230	8.5	275
	Changing1	10.7	202	11.6	221	11.9	299	11.9	299
	Changing2	13.2	219	14.0	260	-[d]	-	-	-
	Changed	13.3	228	14.1	262	14.1	262	13.4	368
VT1300	Current[a]	6.5	132	6.7	153	7.0	220	6.8	260
	Changing1	9.5	184	10.1	209	10.4	262	10.3	289
	Changing2	11.2	212	11.8	228	-[d]	-	-	-
	Changed	11.5	203	12.1	231	12.3	249	11.5	332
MT1100	Current[a]	5.0	103	5.8	150	5.7	206	5.6	223
	Changing1	8.3	174	9.0	192	9.3	230	9.3	270
	Changing2	9.8	152	11.1	233	-[d]	-	-	-
	Changed	9.8	152	11.1	233	11.1	233	10.4	309
VT100	Current[a]	3.2	63	3.8	119	4.0	167	3.9	189
	Changing1	6.9	160	7.1	175	7.3	189	7.7	239
	Changing2	-[d]	-	-	-	-	-	-	-
	Changed	8.2	134	8.6	198	9.1	218	8.9	243
CT1300	Current[a]	3.4	85	3.6	110	3.9	157	3.9	168
	Changing1	6.7	150	7.0	167	7.5	200	7.4	223
	Changing2	-[d]	-	-	-	-	-	-	-
	Changed	7.8	125	8.8	196	8.7	213	8.6	228

[a] Current climate and no climate change.
[b] The figure denotes the average annual timber yield.
[c] The figure includes CO_2 in living merchantable timber at stand.
[d] Second rotation is not needed, since the first already reaches the phase of stabilized climate.

The economic gains of optimal adaptation

Climate change increases bare land values even if the stand management is not optimally adapted to changing climate. However, adaptation yields remarkably higher bare land values (Table 4). In Table 4, CUR denotes the bare land value of stand management that is optimized in current climate and used in changing climate as such, whereas OPT denotes the bare land value of stand management optimally adapted to changing climate. Given zero carbon price and good growth conditions (MT1300, VT1300, MT1100), the bare land value of optimally adapted stand management is on average 23% higher. At poor sites (VT1100, CT1300) the increase is on average is as high as 84%. At positive carbon prices the increase in bare land value is smaller: at good sites on average 10-15% and at poor sites 22-33%, depending on carbon price.

Table 4. Comparison between bare land values obtained from optimization (OPT) and from using in changing climate the optimal solution obtained in current climate assuming no climate change (CUR).

	MT1300			VT1300			MT1100			VT1100			CT1300		
p_c	OPT, €	CUR, €	Gain, %	OPT, €	CUR, €	Gain, %	OPT, €	CUR, €	Gain, %	OPT, €	CUR, €	Gain, %	OPT, €	CUR, €	Gain, %
0	2269	1880	21	1629	1329	23	1249	1005	24	745	319	134	776	573	35
20	3776	3380	12	2859	2390	20	2355	2088	13	1583	1168	36	1547	1178	31
30	4558	4059	12	3498	2926	20	2925	2616	12	2018	1600	26	1952	1505	30
40	5340	4856	10	4156	3655	14	3524	3009	17	2459	1980	24	2358	1809	30
60	7042	6488	9	5539	4860	14	4754	4143	15	3368	2730	23	3180	2559	24
100	10563	9802	8	8412	7637	10	7289	6582	11	5285	4290	23	4964	4113	21

Note: p_c denotes CO_2 price.

4 Discussion

We find the rotation length to decrease with improving growth conditions, when the possibility of thinnings is excluded. Similar results have been reported in the case of genetical improvements of tree seedlings (Löfgren 1985, Wagner and Holmes 1999, Heaps 1981) and increasing timber prices (Newman et al. 1985 and Hardie et al. 1984).

With optimal thinnings, we find the rotation length to first increase with climate change and then to decrease. This result emphasizes the importance of allowing non-uniform rotations, since optimization assuming similar rotations is obviously incapable of providing such a result (see for example Pukkala and Kellomäki 2012). Without including carbon storage, the optimal rotation in the changed climate tends to be longer than in the current climate. This result is supported by Tahvonen et al. (2013), who find that the rotation length can be longer in better growth conditions, because the optimal number of thinnings is higher. Earlier studies with thinning but without optimization report the rotation to shorten with improving growth conditions (see for example Kellomäki and Kolström 1993). Kellomäki et al. (1997a) find the rotation period at Scots pine stands in southern Finland to shorten by 23 years with increasing temperature, when the timing of the clearcut is determined by the mean diameter of the trees. Ahtikoski et al. (2013) find in their stand management optimization study with non-changing climate but improving seed material that the number of thinnings remains the same but thinnings and clearcut were all performed earlier at stands with genetically improved seeds. Similar result is found by Pukkala and Kellomäki (2012) in their optimization of a two-thinning schedule in changing climate.

We find that the climate change causes the optimal number of thinnings to increase, which is probably because with improving growth conditions the timber yield increases and thus the relative importance of fixed harvesting cost decreases. We find the optimal number of thinnings to increase with improving growth conditions even when the optimal rotation shortens. This is supported by Mäkipää et al. (2011), who find the optimal number of thinnings under stable current (changed) climate to be 2 (3) and the optimal rotation to be 80 (54). Briceño-Elizondo et al. (2006a) also suggest the number of thinnings to increase with climate change, but do not explain how it affects the optimal rotation. Our result that the thinnings are performed earlier in changed climate than in current climate is also found in Mäkipää et al. (1999, 2011) and Kellomäki and Kolström (1993) but using rather different approach. Moreover, Briceño-Elizondo et al. (2006b) suggest earlier and more intensive thinnings in changing climate.

We find the average annual timber yield in the optimal results without carbon subsidies to be 68-156% higher in the changed climate compared to the current climate, depending on the site (Table 3). The increase in timber yield is the joint result of improved growth potential and the adaptation in the management. If the stand management would not be adapted, but the stand management that is optimal in current climate would be used in the changed climate, the annual timber yield increased by 42-112%, depending on the site.

Our results concerning the increase in timber yield are in line with the existing literature. Beuker et al. (1996) use a gap type growth model and consider 4°C increase in temperature in 100 years and keep the no-thinning management of Scots pine stands fixed. They find the wood production in northern Finland in changing climate to be 40% higher than presently, but the effect in southern Finland to be minor. Briceño-Elizondo et al. (2006a) use a process-based model and two climate scenarios where in 100 years the temperature increases by 3.7-5.1 °C and precipitation by 17-24 % in southern Finland and by 3.5-4.9 °C and 29-32 % in northern Finland, respectively. Furthermore they assume the carbon dioxide content of the atmosphere to double. With management according to recommendations, they find the timber yield of Scots pine stands in southern (northern) Finland to be

27% (53%) higher in the changing climate. They argue that management change because of climate change could be beneficial, but do not back this with any optimization. Kellomäki et al. (1997a) use somewhat similar climate change specification than Briceño-Elizondo et al. (2006a), but do not consider the possibility to adapt the management. They find the timber yield of Scots pine stands in southern Finland to be 30% higher under climate change.

We find the average carbon stock in living merchantable timber at zero carbon price to be at good sites (MT1300, VT1300, MT1100) on average 51% higher in the changed climate compared to solutions with no climate change. Keeping the management fixed, the stock increases due to climate change at good sites on average by 44%. At poor sites (VT1100, CT1300) the increase in carbon stock due to climate change with optimal adaptation is on average 80%. Interestingly, without adaptation in management, the corresponding figure is higher: 109%. This is probably because the optimal rotation at poor sites in changed climate is shorter than in current climate, contributing to a lower increase in the average carbon stock in the case of optimal adaptation of the management.

The positive effect of climate change to carbon stocks is also found in Garcia-Gonzalo et al. (2007a), who use the same model and climate change specification than Briceño-Elizondo et al. (2006a). They find the average carbon storage in total above- and below-ground tree biomass in Scots pine stands in central Finland to increase by 11-14% with changing climate, depending on the climate scenario used, but regardless of management scenario used. Furthermore, the results for Scots pine in Mäkipää et al. (1999) imply that the average carbon storage in vegetation in southern Finland is about 10% larger in changed climate. They use a gap-type forest model and assume 4°C increase in temperature and 10% increase in precipitation in 100 years and keep the management choice fixed.

In contrast, the results of Mäkipää et al. (2011) for optimally managed Norway spruce stands imply the average carbon stock in stems to be lower in changed climate. This is probably because in their results the optimal rotation was shorter in changed climate than without climate change. This interpretation is backed with the fact that carbon stock in stems increased in their no-management scenario. The results for Scots pine in Karjalainen (1996) imply that the average carbon storage in total living biomass of trees and ground vegetation in southern Finland is smaller in changing climate than without climate change. The growth model in his study seems to underestimate the positive effect of temperature increase to Scots pine growth, since given the same conditions and a more-advanced growth model, Kellomäki et al. (1997a) find the mean annual volume growth of the stem volume in Scots pine stands to increase by 28% with climate change.

This study assumes no stochastic events, such as storm damages, heat waves, fires or pest invasions, which all are predicted to increase in probability because of changing climate (Seidl et al. 2011). Taking their effect into account would necessitate a stochastic model, which is not feasible with a growth model as complex as our process-based model. However, our result of earlier and more frequent thinning as a result of climate change is suggested as a means to reduce risks towards catastrophic events, insects or drought (Bolte et al. 2009).

5 Conclusion

Economic-ecological optimization of forest stand management in changing climate produces new results concerning optimal stand management as well as timber production and carbon storage in changing climate. We find the optimal stand management to be sensitive to the climate change. Climate change causes the optimal number of thinnings to increase, if it is not already at maximum in current conditions without climate change. The optimal rotation tends to lengthen when the optimal number of thinnings increases, but tends to shorten when the optimal number of thinnings stays the same.

Simultaneous optimization of all stand management activities in changing climate enables us to fully capture the potential of improving growth conditions. We therefore find notably higher increases in timber production and carbon storage than earlier studies without optimization. However, because these changes are so high, we must acknowledge that the current version of the growth model in changed climate possibly overestimates the growth increase caused by the climate change. In our results, optimally adapted stand management yields significantly better land values compared to benchmark management. Our model can be augmented to include forest soil dynamics and biodiversity consideration.

The detailed stand management optimization approach used in this study can be used to improve the accuracy of studies concerning the prediction of the change in tree species selection over wide geographical areas (Hanewinkel et al. 2010, 2012). Modeling species distribution change due to climate change only using logistic regression based on national forest inventory data neglects the stand management adaptation potential. Our approach can also be utilized to fully capture the economic value of adaptation. Guo and Costello (2013) find the value of adaptation by changing management to be minor, but regard changing rotation as the only means to adapt the management. At least in Nordic conditions this is a serious limitation that may drastically underestimate the value of adaptation, and thus the full adaptation possibilities in forestry.

Acknowledgements

We thank Academy of Finland for the financial support.

Appendix A. Cost and price details

Stand establishment activities include land preparation at year 1 (142 € ha^{-1}), seeding at year 2 (176 € ha^{-1}) (except at the site CT1300, where a costless natural regeneration is assumed), and tending of the seedling stand at year 13-20 (276 € ha^{-1}), depending on the site. Stand establishment costs are the same for all initial densities. Logging costs are a function of the volumes of saw logs, pulpwood, and waste wood, as well as of the number of trees harvested (See Hyytiäinen et al. 2004 for further information). The fixed harvesting cost is €300, the annual administration costs €11, and the capital income tax rate 28%. Prices of timber assortments are given as roadside prices and they are listed in Table A1.

Appendix references

Hyytiäinen, K., Hari, P., Kokkila, T., Mäkelä, A., Tahvonen, O., and Taipale, J. 2004. Connecting a process-based forest growth model to stand-level economic optimization. Can. J. For. Res. **34**(10): 2060-2073. doi:10.1139/x04-056.

Table A1. The roadside prices of timber assortments.

A-grade saw timber (€ m^{-3})	69.03
B-grade saw timber (€ m^{-3})	51.13
C-grade saw timber (€ m^{-3})	38.35
Pulp from logs (€ m^{-3})	24.09
Pulp from tree tops (€ m^{-3})	24.09

References

Ahtikoski, A., Salminen, H., Ojansuu, R., Hynynen, J., Kärkkäinen, K., and Haapanen, M. 2013. Optimizing stand management involving the effect of genetic gain: preliminary results for Scots pine in Finland. Can. J. For. Res. **43**(3): 299-305. doi:10.1139/cjfr-2012-0393.

Bergström, I., Mattsson, T., Niemelä, E., Vuorenmaa, J., and Forsius, M. (Editors). 2011. Ekosysteemipalvelut ja elinkeinot – haavoittuvuus ja sopeutuminen muuttuvaan ilmastoon. VACCIA-hankkeen yhteenvetoraportti. Suomen ympäristökeskus. Helsinki. Suomen ympäristö 26/2011. Available from https://helda.helsinki.fi/bitstream/handle/10138/37028/SY_26_2011_low-res.pdf?sequence=3 [accessed 15 January 2014]. [In Finnish].

Beuker, E., Kolström, M., and Kellomäki, S. 1996. Changes in Wood Production of Picea abies (L.) Karst. and Pinus sylvestris (L.) Under Climate Change: Comparison of Field Measurements and Results of Mathematical Model. Silva Fennica **30**: 159–166.

Bolte, A., Ammer, C., Lof, M., Madsen, P., Nabuurs, G., and Schall, P. 2009. Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. Scand. J. For. Res., **24**: 473–482.

Briceño-Elizondo, E., Garcia-Gonzalo, J., Peltola, H., Matala, J., and Kellomäki, S. 2006a. Sensitivity of growth of Scots pine, Norway spruce and silver birch to climate change and forest management in boreal conditions. For. Ecol. Manage. **232**: 152–167.

Briceño-Elizondo, E., Garcia-Gonzalo, J., Peltola, H., and Kellomäki, S. 2006b. Carbon stocks and timber yield in two boreal forest ecosystems under current and changing climatic conditions subjected to varying management regimes. Environmental Science and Policy. **9**: 237-252.

Cajander, A.K. 1949. Forest types and their significance. Acta For. Fenn. **56**(5): 1-71. Available from http://hdl.handle.net/10138/17982 [accessed 15 January 2014].

Garcia-Gonzalo, J., Peltola, H., Briceño-Elizondo, E., and Kellomäki, S. 2007a. Changed thinning regimes may increase carbon stock under climate change: a case study from a Finnish boreal forest. Clim. Change **81**: 431–454.

Garcia-Gonzalo, J., Peltola, H., Zubizarreta Gerendiain, A., and Kellomäki, S. 2007b. Impacts of forest landscape structure and management on timber production and carbon stocks in the boreal forest ecosystem under changing climate. For. Ecol. Manage. **241**: 243-257.

Garcia-Gonzalo, J., Jäger, D., Lexer, M., Peltola, H., Briceño-Elizondo, E., and Kellomäki, S. 2008. Does climate change affect optimal planning solutions for multi-objective forest management? Forst Jagdzeitung **179**(5–6): 77–94.

Getz, W.M., and Haight, R.G. 1989. Population harvesting: demographic models of fish, forest and animal resources. Princetown University Press, Princetown, New Jersey.

Goetz, R.U., Hritonenko, N., Mur, R., Xabadia, À., and Yatsenko, Y. 2013. Forest management for timber and carbon sequestration in the presence of climate change: The case of Pinus Sylvestris. Ecol. Econ. **88:** 86-96.

Guo, C., and Costello, C. 2013. The value of adaption: Climate change and timberland management. J. Environ. Econ. Manage. **65**(3):452-468.

Haight, R.G., Brodie, J.D., and Dahms, W.G. 1985. A dynamic programming algorithm for optimization of lodgepole pine management. For. Sci. **31**(2): 321–330.

Hanewinkel, M., Hummel, S., and Cullmann, D.A. 2010. Modelling and economic evaluation of forest biome shifts under climate change in Southwest Germany. For. Ecol. Manage. **259**: 710–719.

Hanewinkel. M., Cullmann, D.A., Schelhaas M.-J., Nabuurs G.-J., and Zimmermann N.E. 2012. Climate change may cause severe loss in the economic value of European forest land. Nature Climate Change, doi: 10.1038/nclimate1687.

Hardie, I.W., Daberkow, J.N., and McConnell, K.E. 1984. A timber harvesting model with variable rotation lengths. For. Sci. **30**: 511-523.

Heaps, T. 1981. The qualitative theory of optimal rotations. Can. J. Econ. **14**: 686-699.

Hyytiäinen, K., Hari, P., Kokkila, T., Mäkelä, A., Tahvonen, O., and Taipale, J. 2004. Connecting a process-based forest growth model to stand-level economic optimization. Can. J. For. Res. **34**(10): 2060-2073. doi:10.1139/x04-056.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jylhä, K., Ruosteenoja, K., Räisänen, J., Venäläinen, A., Tuomenvirta, H., Ruokolainen, L., Saku, S., and Seitola, S. 2009. The changing climate in Finland: estimates for adaptation studies. Finnish Meteorological Institute, Reports 2009:4. Available from https://helda.helsinki.fi/bitstream/handle/10138/15711/2009nro4.pdf?sequence=1 [accessed 15 January 2014]. [In Finnish].

Karjalainen, T. 1996. Dynamics and potentials of carbon sequestration in managed stands and wood products in Finland under changing climatic conditions. For. Ecol. Manage. **80**: 113–132.

Kellomäki, S., and Kolström, M. 1993. Computations on the yield of timber by Scots pine when subjected to varying levels of thinning under changing climate in southern Finland. For. Ecol. Manage. **59**: 237–255.

Kellomäki, S., Karjalainen, T., and Väisänen, H. 1997a. More timber from boreal forests under changing climate? For. Ecol. Manage. **94**: 195–208.

Kellomäki S., Väisänen H., and Kolström T. 1997b. Model computations on the effects of elevating temperature and atmospheric CO2 on the regeneration of Scots pine at the timber line in Finland. Clim. Change, **37**: 683–708.

Kolda, T.G., Levis, R.M. and Torczon, V. 2003. Optimizing by direct search: new perspectives on some classical and modern methods. SIAM Review **35**: 385-482.

Liski, J., Pussinen, A., Pingoud, K., Mäkipää, R., and Karjalainen, T. 2001. Which rotation length is favourable to carbon sequestration? Can. J. For. Res. **31**(11): 2004-2013. doi:10.1139/x01-140.

Lutz, D.A., Shugart, H.H., and White, M.A. 2013. Sensitivity of Russian forest timber harvest and carbon storage to temperature increase. Forestry **86**: 283-293.

Löfgren, K.-G. 1985. Effect on the socially optimal rotation period in forestry of biotechnological improvements of the growth function. For. Ecol. Manage. **10**: 233–249.

Matala, J., Ojansuu, R., Peltola, H., Raitio, H., and Kellomäki, S. 2006. Modelling the response of tree growth to temperature and CO2 elevation as related to the fertility and current temperature sum of a site. Ecol. Modell. **199**: 39–52.

McConnell, K.E., Daberkow, J.N., and Hardie, I.W. 1983. Planning timber production with evolving prices and costs. Land Econ. **59**: 292-299.

Millar, C.I., Stephenson, N.L., and Stephens, S.L. 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications **17**: 2145–2151.

Mäkelä, A. 1997. A carbon balance model of growth and self-pruning in trees based on structural relationships. For. Sci. **43**(1): 7-24.

Mäkelä, A. 2002. Derivation of stem taper from the pipe theory in a carbon balance framework. Tree Physiol. **22**(13): 891-905. Available from http://treephys.oxfordjournals.org/content/22/13/891 [accessed 15 January 2014].

Mäkelä, A., and Mäkinen, H. 2003. Generating 3D sawlogs with a process-based growth model. For. Ecol. Manage. **184**(1-3): 337-354. doi:10.1016/S0378-1127(03)00152-X.

Mäkipää, R., Karjalainen, T., Pussinen, A., and Kellomäki, S. 1999. Effects of climate change and nitrogen deposition on the carbon sequestration of a forest ecosystem in the boreal zone. Can. J. For. Res. **29**: 1490–1501.

Mäkipää, R., Linkosalo, T., Niinimäki, S., Komarov, A., Bykhovets, S., Tahvonen, O., and Mäkelä, A. 2011. How forest management and climate change affect the carbon sequestration of a Norway spruce stand. J. For. Plann. **16**: 107–120.

Newman, D.H., Gilbert, C.E., and Hyde, W.F. 1985. The optimal rotation with evolving prices. Land Econ. **61**: 357-394.

Nuutinen, T., Matala, J., Hirvelä, H., Härkönen, K., Peltola, H., Väisänen, H., and Kellomäki, S. 2006. Regionally optimized forest management under changing climate. Clim. Change **79**: 315–333.

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., and Wagner, F. (Editors). 2003. Good practice guidance for land use, land-use change and forestry. Intergovernmental Panel on Climate Change: IPCC National Greenhouse Gas Inventories Programme. Kanagawa Japan: Institute for Global Environmental Strategies (IGES) for the IPCC. Available from http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.htm [accessed 15 January 2014].

Pihlainen, S., Tahvonen, O., and Niinimäki, S. 2014. The economics of timber and bioenergy production and carbon storage in Scots pine stands. Can. J. For. Res. **44**(9): 1091-1102. doi: 10.1139/cjfr-2013-0475.

Pukkala, T., and Kellomäki, S. 2012. Anticipatory vs. adaptive optimization of stand management when tree growth and timber prices are stochastic. Forestry **85**:463–472.

Pussinen, A., Karjalainen, T., Mäkipää, R., Valsta, L., and Kellomäki, S. 2002. Forest carbon sequestration and harvests in Scots pine stand under different climate and nitrogen deposition scenarios. For. Ecol. Manage. **158**: 103–115.

Ruosteenoja, K., Räisänen, J., and Pirinen, P. 2011. Projected changes in thermal seasons and the growing season in Finland. Int. J. Climatol. **31**: 1473–1487. doi:10.1002/joc.2171.

Seidl, R., Fernandes, P.M., Fonseca, T.F., Gillet, F., Jönsson, A.M., Merganičová, K., Netherer, S., Arpaci, A., Bontemps, J.-D., Bugmann, H., González-Olabarria, J.R., Lasch, P., Meredieu, C., Moreira, F., Schelhaas, M.-J., and Mohren, F. 2011. Modelling natural disturbances in forest ecosystems: a review. Ecol. Model. **222**(4): 903–924. doi:10.1016/j.ecolmodel.2010.09.040.

Sohngen, B., and Mendelsohn, R. 1998. Valuing the impact of large-scale ecological change in a market: the effect of climate change on US timber, Amer. Econ. Rev. **88**(4): 686–710.

Tahvonen, O., Pihlainen, S., and Niinimäki, S. 2013. On the economics of optimal timber production in boreal Scots pine stands. Can. J. For. Res. **43**(8): 719-730. doi: 10.1139/cjfr-2012-0494.

The MathWorks, Inc. 2013. Global optimization toolbox user’s guide R2013b. [online]. Available from http://www.mathworks.com/help/pdf_doc/gads/gads_tb.pdf [accessed 25 February 2014].

Wagner, J.E., and Holmes, T.P. 1999. Estimating economic gains for landowners due to time-dependent changes in biotechnology. For. Sci. **45**(2): 163–170.