Puuntuotoksen ja hiilensidonnan ekologis-taloudellinen optimointi sekä ilmastonmuutokseen sopeutuminen suomalaisissa mäntymetsiköissä

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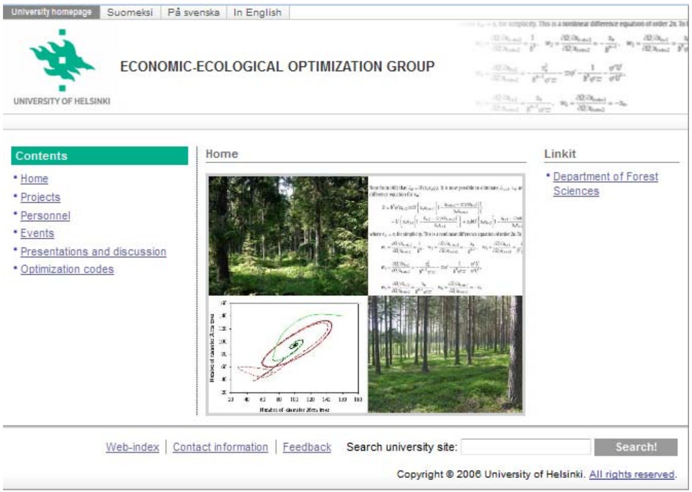
Taloudellis-ekologinen tutkimusryhmä (Olli Tahvonen)
http://blogs.helsinki.fi/ee-opt/



Dissertationes Forestales #

Economics of boreal Scots pine management under changing climate

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Academic dissertation

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public criticism in XXX on XXX at 12 o'clock noon.

Article 1:

719
NRC Research Press
ARTICLE

On the economics of optimal timber production in boreal Scots pine stands

Olli Tahvonen, Sampo Pihlainen, and Sami Niinimäki

Can. J. For. Res. 43: 719–730 (2013) dx.doi.org/10.1139/cjfr-2012-0494
Published at www.nrcresearchpress.com/cjfr on 3 May 2013.

Earlier studies on economic optimization of Scots pine stand management:

Whole stand models

- Stand volume is function of stand age
    - Nyyssönen (1958, Commun. Inst. For. Fenn.)
    - Kilkki and Väisänen (1969, Acta For. Fenn.)
    - Gong (1998, For. Sci.)
    - Brukas and Brodie (1999, Balt. For.)
    - Brazee and Bulte (2000, For. Sci.)
    - Lu and Gong (2003, J. For. Econ.)

Individual-tree models

- Each tree characterized by a number of state variables
- Harvesting and interaction with neighboring trees explicitly affects individual tree growth
    - Eriksson (1999, Scand. For. Econ.)
    - Pukkala and Miina (1998, Can. J. For. Res.)
    - Hyytiäinen et al. (2004, Can. J. For. Res; 2005, For. Sci.)
    - Pohjola & Valsta (2007, Forest Policy Econ.)

Gaps in the literature:

1. Results not provided for all relevant Nordic sites
2. Limited results on optimal thinnings
    - Except Hyytiäinen et al. (2004, Can. J. For. Res; 2005, For. Sci.) Pohjola & Valsta (2007, Forest Policy Econ.)
    - Thinnings may account for 40% of the overall revenue
3. Neglect of timber quality effects
    - Except Hyytiäinen et al. (2004, Can. J. For. Res)
4. Growth model's reliability limits
    - Statistical-empirical vs process-based models

Our model extends from:

Connecting a process-based forest growth model to stand-level economic optimization

Kari Hyytiäinen, Pertti Hari, Tero Kokkila, Annikki Mäkelä, Olli Tahvonen, and Juhani Taipale

Can. J. For. Res. 34: 2060–2073 (2004) doi: 10.1139/X04-056 © 2004 NRC Canada

By:

- Providing results for all relevant Nordic sites
- Optimizing also initial density
- Refining thinning specification
- Using a more efficient optimization algorithm

Economic-ecological optimization, vol.1

Numerical optimization of Scots pine stand management with extended Faustmann framework including

- thinnings
- five merchantable timber assortments (based on information about branches)
- detailed harvesting cost models

The size-age-structured rotation model:

$$\max_{\substack{\{N_0, k, t_s, \gamma_{dt_s},\\ d=1,2,3, s=1,\ldots,k\}}} J = \left\{ \frac{\sum_{s=1}^{k} b^{t_s} \left\{ \sum_{i=1}^{n} \sum_{v=1}^{g} p_v D_{ivt_s} h_{it_s} - C\left(\mathbf{h}_{t_s}, \mathbf{D}_{t_s}\right) \right\} - w}{1 - b^{t_k}} - \frac{A}{r} \right\} (1-\rho),$$

subject to
the process-based growth model* (7920-18320 difference equations).

Recall the generic Faustmann:

$$\max_{\{t\}} J(t) = \frac{b^t p x_t - w}{1 - b^t}$$

Optimized variables: initial density; rotation period;
number, timing, type and intensity of thinnings

} OPTIMIZED SIMULTANEOUSLY

Number of optimized variables is 3-22.

Source:

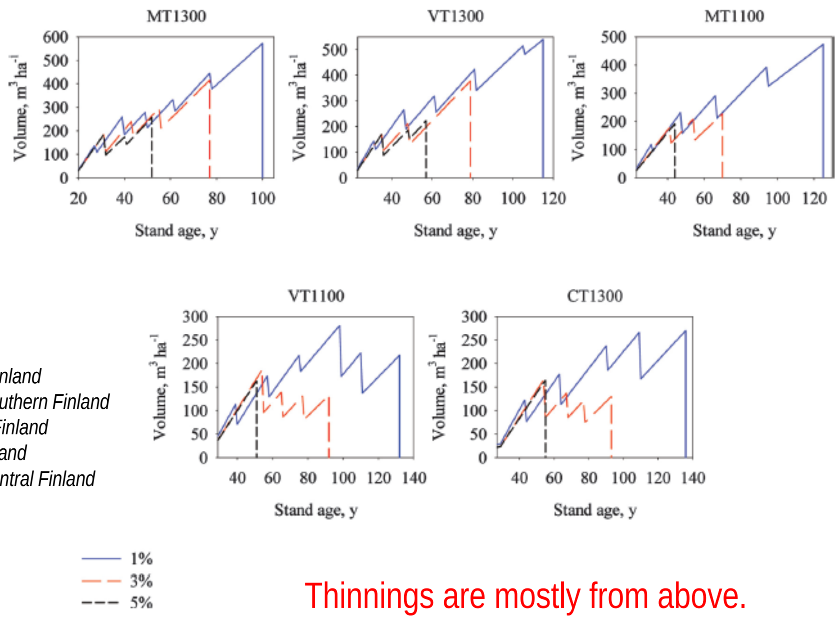
On the economics of optimal timber production in boreal Scots pine stands

Olli Tahvonen, Sampo Pihlainen, and Sami Niinimäki Can. J. For. Res. 43: 719–730 (2013) dx.doi.org/10.1139/cjfr-2012-0494

*Mäkelä (2002) and Mäkelä and Mäkinen (2003)

Results

Fig. 9. Volume development under bare land value maximization.



MT1300 = Fertile site in Southern Finland
VT1300 = Average fertility site in Southern Finland
CT1300 = Infertile site in Southern Finland
MT1100 = Fertile site in Central Finland
VT1100 = Average fertility site in Central Finland

MSY or interest rate	Optimal no. of seedlings
MT1300	
MSY	3000
0%	3000
1%	3000
2%	3000
3%	2000
4%	2000
5%	2000
VT1300	
MSY	3000
0%	3000
1%	3000
2%	3000
3%	2000
4%	2000
5%	2000
MT1100	
MSY	3000
0%	3000
1%	3000
2%	3000
3%	1500
4%	1500
5%	1500
VT1100	
MSY	3000
0%	3000
1%	3000
2%	1500
3%	1500
4%	1500
5%	1500
CT1300	
MSY	3000
0%	3000
1%	3000
2%	1500
3%	1500
4%	1500
5%	1500

Thinnings are mostly from above.
(cf. Zeide 2001)

Notice the effect of interest rate and growth conditions to optimal…
- thinnings
- rotation period
- development of stand density
- initial density

Source:

On the economics of optimal timber production in boreal Scots pine stands

Olli Tahvonen, Sampo Pihlainen, and Sami Niinimäki Can. J. For. Res. 43: 719–730 (2013) dx.doi.org/10.1139/cjfr-2012-0494

Article 2:

1091

NRC Research Press

ARTICLE

The economics of timber and bioenergy production and carbon storage in Scots pine stands

Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki

Can. J. For. Res. 44: 1091–1102 (2014) dx.doi.org/10.1139/cjfr-2013-0475

Published at www.nrcresearchpress.com/cjfr on 6 May 2014.

Earlier studies on economic optimization of timber production and carbon storage in Scots pine stands:

For uneven-aged stands

- Goetz et al. (2010, For. Sci.)

Optimizing only rotation length (in even-aged stands)

- Gong and Kriström (1999, SLU Inst. Skogsekon., Arbetsrap.)
- Caparrós et al. (2003, Int. J. Sust. Dev.)

Optimizing rotation length and thinnings (in even-aged stands)

- Pohjola and Valsta (2007, Forest Policy Econ.)

Gaps in the literature:

1. Neglect of thinnings
   - Except: Pohjola & Valsta (2007, Forest Policy Econ.)
2. Deficient carbon pool
3. No results on bioenergy vs carbon storage in harvest residues (for any tree species)
   - cf. Bjornstad & Skonhoft (2002, Environ. Resour. Econ.) for Norway spruce
4. No country-level cost functions (for any tree species)
5. No results on optimal method for carbon storage in Finland
   - Forest management adaptation or afforestation?

Our model extends from:

On the economics of Norway spruce stands and carbon storage

Sami Niinimäki, Olli Tahvonen, Annikki Mäkelä, and Tapio Linkosalo

Can. J. For. Res. 43: 637–648 (2013) dx.doi.org/10.1139/cjfr-2012-0516

By:

- Providing results for Scots pine
- Including carbon storage in branches, foliage, and dead trees
- Including bioenergy production

Carbon credits and management of Scots pine and Norway spruce stands in Finland

J. Pohjola [a,*], L. Valsta [b,1]

Forest Policy and Economics 9 (2007) 789 – 798

By:

- Using a process-based growth model
- Including six timber assortments instead of two
- Including carbon storage in products and in dead trees
- Including bioenergy production

Economic-ecological optimization, vol.2

The framework is extended with

- CO_2 subsidy system with decaying dead trees and timber products
- Bioenergy

The size-age-structured rotation model:

$$\max_{\substack{\{N_0,k,t_s,\gamma_{dt_s},\gamma_{bt_s}\} \\ \{d=1,2,3,s=1,\dots,k\}}} J = \left\{ \frac{\sum_{s=1}^{k} b^{t_s} \left\{ \sum_{i=1}^{n} \left[\sum_{v=1}^{g} p_v D_{ivt_s} h_{it_s} + p_b D_{ibt} h_{it_s} \gamma_{bt_s} \right] - C\left(\mathbf{h}_{t_s}, \mathbf{D}_{t_s}\right) \right\} + \sum_{t=0}^{t_k} b^t p_c Q_t - w}{1 - b^{t_k}} - \frac{A}{r} \right\} (1-\rho),$$

subject to
the process-based growth model* (7920-18320 difference equations).

Optimized variables: initial density; rotation period;
number, timing, type and intensity of thinnings

Number of optimized variables is 4-28.

Source:

The economics of timber and bioenergy production and carbon storage in Scots pine stands

Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki

Can. J. For. Res. 44: 1091–1102 (2014) dx.doi.org/10.1139/cjfr-2013-0475

*Mäkelä (2002) and Mäkelä and Mäkinen (2003)

CO_2 subsidy systems

Monetary value via subsidy-based instrument

$$Q_t = \mu \sum_{i=1}^{n} \left\{ \begin{array}{l} \sum_{\psi=1}^{3} \left\{ q_{i\psi t} z_{i1t} - q_{i\psi,t-1} z_{i1,t-1} + \left[1-\alpha_\psi(r)\right] q_{i\psi t} \left[\left(z_{i1,t-1} - h_{it} - z_{i1t} \right) + \omega_\psi \left(1-\gamma_{bt}\right) h_{it} \right] \right\} \\ + \sum_{\phi=1}^{3} \left\{ \left[1-\beta_\phi(r)\right] x_{i\phi t} \eta_\phi h_{it} \right\} \end{array} \right\}$$

Gross subsidy: Carbon in timber products never decays, $\beta = 0$

Net subsidy: Carbon in timber products decays at some rate, $0 < \beta \leq 1$

Gross subsidy system

- Rewards for the carbon stored in net growth

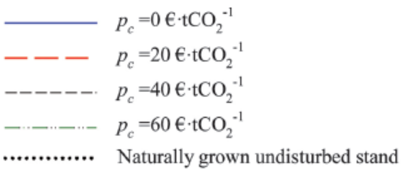
Net subsidy system

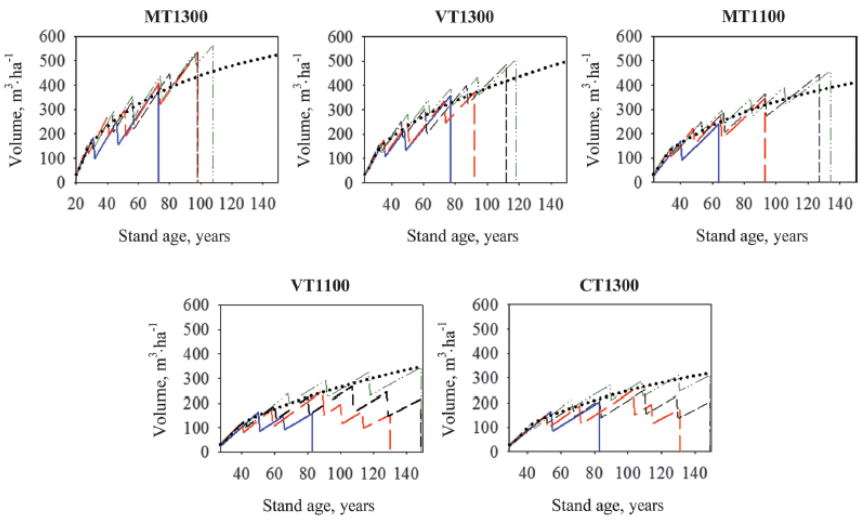
- = gross subsidy – carbon released from timber products
- Similar to the scheme currently enforced in New Zealand

Source:
The economics of timber and bioenergy production and carbon storage in Scots pine stands
Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki
Can. J. For. Res. 44: 1091–1102 (2014) dx.doi.org/10.1139/cjfr-2013-0475

Results

Net subsidy system, interest rate 3%.





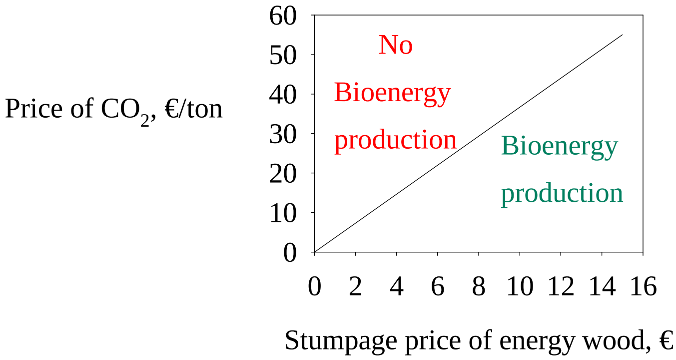
MT1300 = Fertile site in Southern Finland
VT1300 = Average fertility site in Southern Finland
CT1300 = Infertile site in Southern Finland
MT1100 = Fertile site in Central Finland
VT1100 = Average fertility site in Central Finland

The optimal number of thinnings and rotation length increase with CO_2 price.

Source:
The economics of timber and bioenergy production and carbon storage in Scots pine stands
Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki
Can. J. For. Res. 44: 1091–1102 (2014) dx.doi.org/10.1139/cjfr-2013-0475

Results: Bioenergy vs carbon storage in harvest residues

Bioenergy is produced from residues and small-diameter trees from all harvests.



Average fertility site in Southern Finland, interest rate 3%

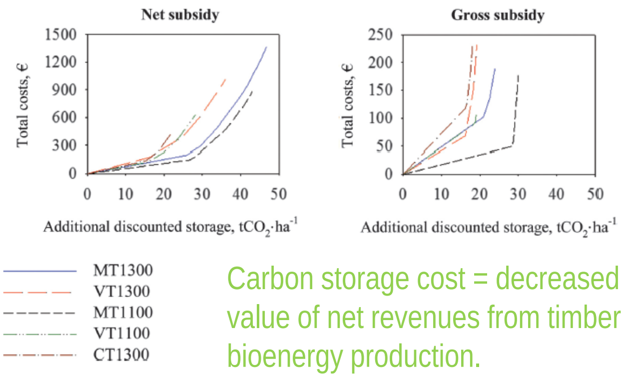
Break-even-curve for bioenergy harvest.

At zero CO_2 price, it is always optimal to harvest bioenergy.

Source:
The economics of timber and bioenergy production and carbon storage in Scots pine stands
Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki
Can. J. For. Res. 44: 1091–1102 (2014) dx.doi.org/10.1139/cjfr-2013-0475

Results: Optimal allocation of carbon storage over different sites

Costs per one hectare of each site type



Carbon storage cost = decreased present value of net revenues from timber and bioenergy production.

MT1300: 1 055 937 ha
VT1300: 661 978 ha
CT1300: 77 598 ha
MT1100:1 625 614 ha
VT1100: 1 351 164 ha

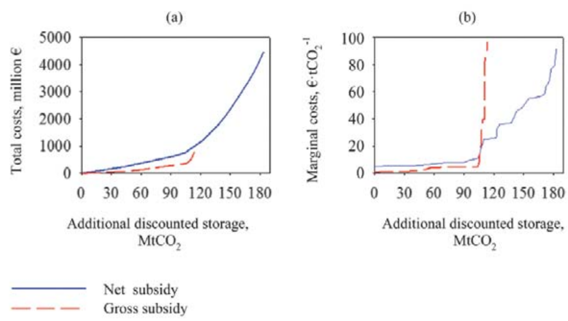
Optimization problem:

$$\min_{\{E_i, i=1...,K\}} V = \sum_{i=1}^{K} C_i\left(E_i\right)$$

s.t.

$$\sum_{i=1}^{K} E_i \geq \bar{E}$$

National costs



Marginal costs are low compared to earlier studies:

- Van Kooten et al. (2009): forestry
- Richards & Stokes (2004): forestry
- Ekholm (2010): ETS- and non-ETS-sectors

Source:
The economics of timber and bioenergy production and carbon storage in Scots pine stands
Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki
Can. J. For. Res. 44: 1091–1102 (2014) dx.doi.org/10.1139/cjfr-2013-0475

Article 3:

Economics of boreal Scots pine management under changing climate (Manuscript)

Sampo Pihlainen[1*]
Olli Tahvonen[1]
Annikki Mäkelä[1]

Earlier studies on economic optimization of Scots pine stand management in changing conditions:

Management scenario comparisons in changing climate:

- Kellomäki and Kolström (1993, For. Ecol. Manage.)
- Kellomäki et al. (1997, For. Ecol. Manage.)
- Nuutinen et al. (2006, Clim. Change)
- Briceño-Elizondo et al. (2006, For. Ecol. Manage.)
- Briceño-Elizondo et al. (2006, Environmental Science and Policy)
- Garcia-Gonzalo et al. (2007, Climatic Change)
- Garcia-Gonzalo et al. (2007, Ecol. Modell.)
- Garcia-Gonzalo et al. (2007, For. Ecol. Manage.)
- Garcia-Gonzalo et al. (2008, Forst Jagdzeitung)
- Alam et al. (2008, Scand. J. For. Res.)

Optimization of forest management in changing conditions:

- Pukkala and Kellomäki (2012, Forestry) (optimization with two thinnings in changing climate, all rotations equal)
- Goetz et al. (2013, Ecol. Econ.) (uneven-aged in changing climate)

- McConnell et al. (1983, Land Econ.) (evolving timber prices and costs in current climate)
- Löfgren (1985, For. Ecol. Manage.) (biotechnological improvements in current climate)

Gaps in the literature:

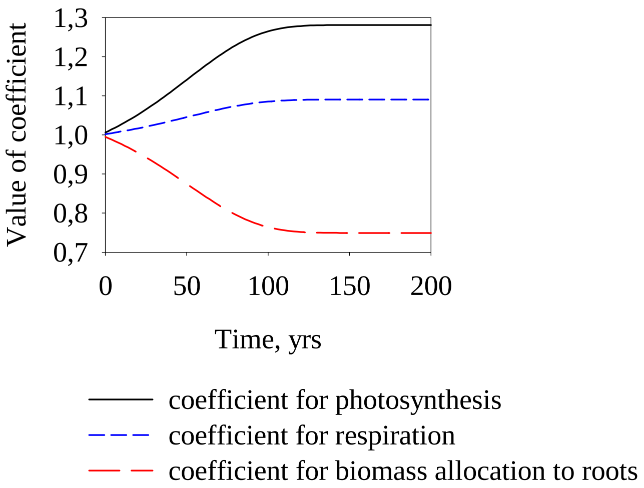
1. No dynamic optimization in changing climate*
   - except
     - Pukkala and Kellomäki (2012, Forestry) (all rotations equal)
     - Goetz et al. (2013, Ecol. Econ.) (uneven-aged)
2. No optimization of thinnings*
   - except Pukkala and Kellomäki (2012, Forestry) (fixed number of thinnings)
3. No carbon storage objective*
4. Value of adaptation controversial*
   - cf. Guo and Costello (2013, JEEM)

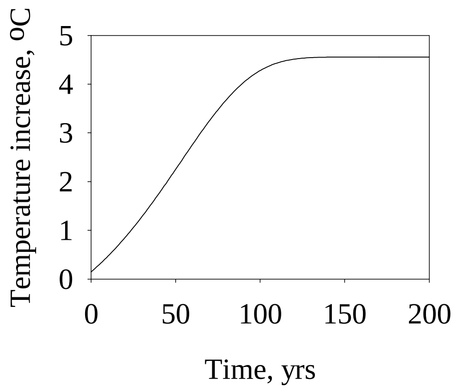
*Gap exists for any tree species

This is the first study of economic optimization of even-aged forest management under changing climate

- to allow successive rotations to change with climate change
- to include carbon storage objective

Model: growth model





Growth model includes a direct link between tree growth and climate change.

Model: optimization problem

The size-age-structured rotation model in changing climate:

$$\max_{\substack{N_{0_a}, k_a, t_{s_a}, \\ \gamma_{dt_{s_a}}, d=1,2,3, \\ s_a=1,\dots,k_a, \\ a=1,2,3}} V = \left(W_1 + b^{t_{k_1}} W_2 + b^{t_{k_1}+t_{k_2}} W_3 - \frac{A}{r}\right)(1-\rho) + b^{t_{k_1}+t_{k_2}+t_{k_3}} \tilde{J},$$

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

subject to
the process-based growth model* (7920-18320 difference equations).

Optimized variables for each rotation: initial density; rotation period;
number, timing, type and intensity of thinnings

*Mäkelä (2002) and Mäkelä and Mäkinen (2003)

Results: without thinnings

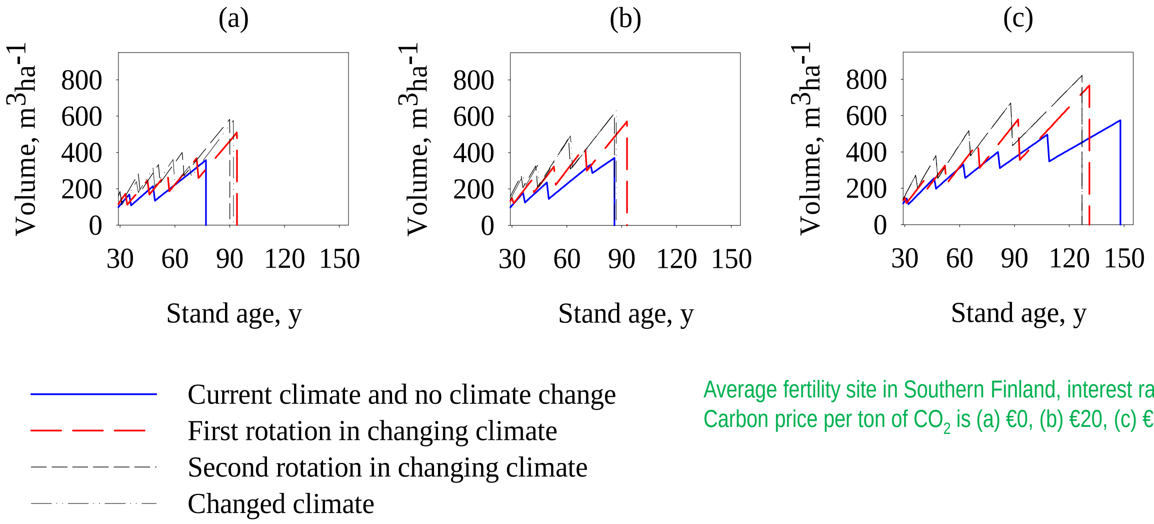
	Climate specification	Current	Changing			Changed
			1st rotation	2nd rotation	3rd rotation	
Fertile site	MT1300	40	37	38	37	36
	VT1300	47	46	40	40	39
	MT1100	49	46	44	44	41
	VT1100	55	53	49	-	47
Infertile site	CT1300	61	52	51	-	54

When no thinnings are allowed, optimal rotations shorten with changing climate.

Interest rate 3%

MT1300 = Fertile site in Southern Finland
VT1300 = Average fertility site in Southern Finland
MT1100 = Fertile site in Central Finland
VT1100 = Average fertility site in Central Finland
CT1300 = Infertile site in Southern Finland

Results: with thinnings



Average fertility site in Southern Finland, interest rate 3%.
Carbon price per ton of CO_2 is (a) €0, (b) €20, (c) €100.

(a) With optimal thinnings and without carbon subsidies
- optimal rotation first lengthens with changing climate, then shortens
- optimal rotation in changed climate is longer than in current climate
- optimal number of thinnings increases

(b-c) With optimal thinnings and with high carbon subsidies
- optimal rotation shortens with changing climate

Results: value of adaptation

p_c	MT1300			VT1300			MT1100			VT1100			CT1300		
	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.

Adaptation yields notably higher bare land values.

Interest rate 3%

MT1300 = Fertile site in Southern Finland
VT1300 = Average fertility site in Southern Finland
MT1100 = Fertile site in Central Finland
VT1100 = Average fertility site in Central Finland
CT1300 = Infertile site in Southern Finland