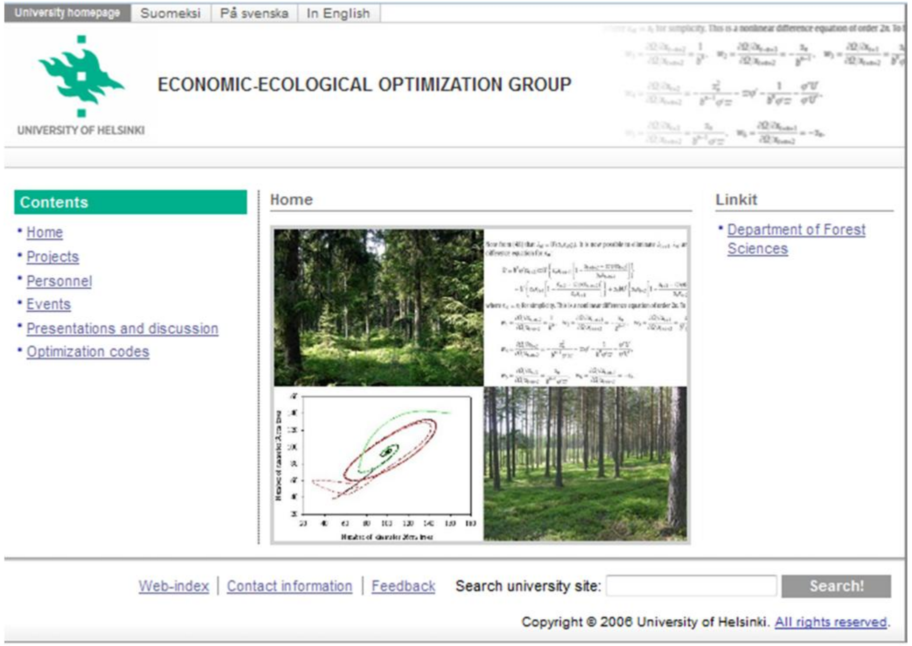
The economics of timber and bioenergy production and carbon storage in Scots pine stands

Sampo Pihlainen[1]*
Olli Tahvonen[1]
Sami Niinimäki[1]

[1] *Department of Forest Sciences, University of Helsinki, Latokartanonkaari 7, PL 27, 00014*
**sampo.pihlainen@helsinki.fi*

Economic-ecological optimization group (Olli Tahvonen)
http://blogs.helsinki.fi/ee-opt/



Copyright © 2006 University of Helsinki. All rights reserved.

Research consortium funded by the Academy of Finland as a part of Finnish Climate Change Research Programme (FICCA)

Economically Optimal Adaptation of Forest Management in the Changing Climate (EconAda)

- Raisa Mäkipää (coordinator), Tapio Linkosalo, et al., Finnish Forest Research Institute (Metla)

- Olli Tahvonen (principal investigator), Sampo Pihlainen et al., University of Helsinki

Dissertationes Forestales #

Economics of boreal Scots pine management under changing climate

Sampo Pihlainen

Department of Forest Sciences

Faculty of Agriculture and Forestry

University of Helsinki

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.

Articles in my thesis

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

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

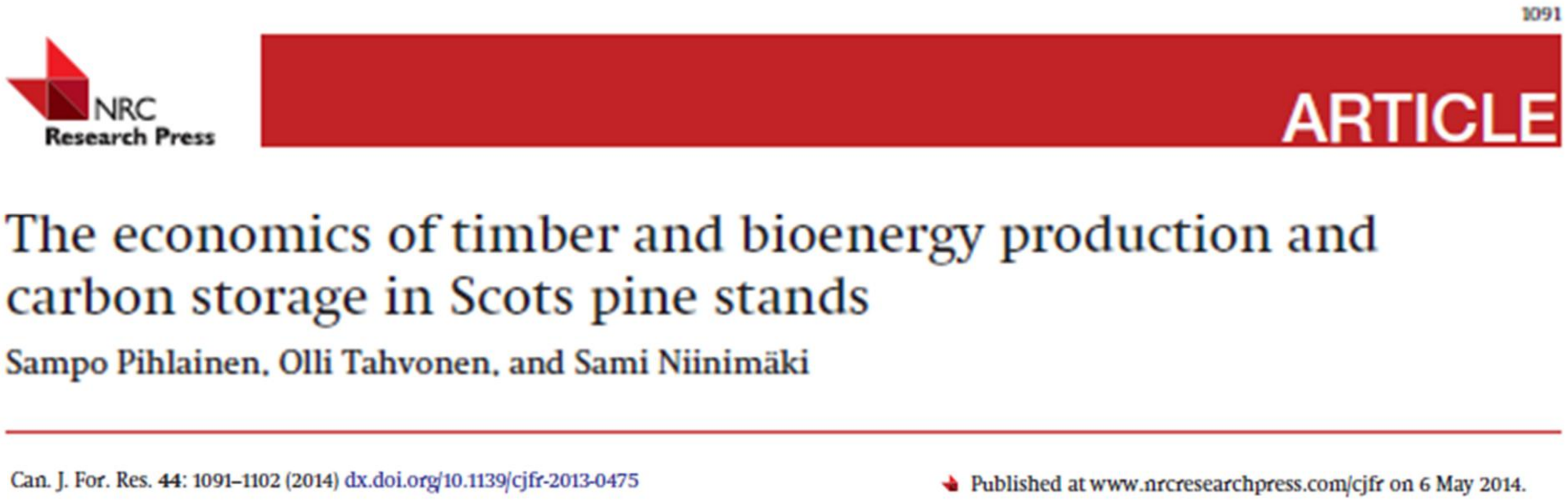
Can. J. For. Res. **44**: 1091–1102 (2014) dx.doi.org/10.1139/cjfr-2013-0475

3

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

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

Article 2:



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

Introduction

Climate change poses an immense challenge to the mankind.

- Forests have an outstanding role in its mitigation (IPCC 2007)
- Current decisions anticipate future growth conditions for a long time horizon

Scots pine (*Pinus sylvestris* L.) is one of the most abundant tree species in the world

- Its significance increases with climate change because of its heat tolerance (Lutz et al. 2013)

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 initial density (in even-aged stands)

- Zhou (2001, J. For. Econ.)

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

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

Recall the generic Faustmann:

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

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

OPTIMIZED SIMULTANEOUSLY

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, $0 < \beta \leq 1$

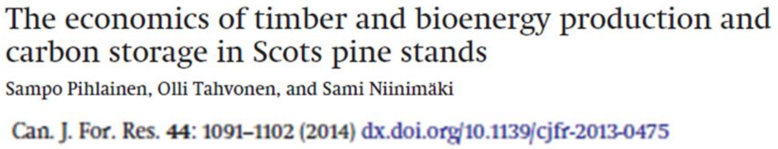
Gross subsidy system

- 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

Ecological model

Detailed process-based growth model for even-aged stands (Mäkelä & al. 1997):

=>causal relationships instead of statistical correlations

Detailed carbon cycle – carbon from photosynthesis is divided between respiration, senescence and growth

Predicts stand growth for the most important site types in Nordic countries

Predicts growth in states outside the validity of statistical models

Numerical optimization

Derivate-free optimization algorithms: a generalized pattern search (Matlab)

Typical number of initial guesses was 50

For one computer processor, finding an optimal solution candidate takes anything between 50 and 530 hours.

RESULTS

The effects of carbon pricing on optimal stand management

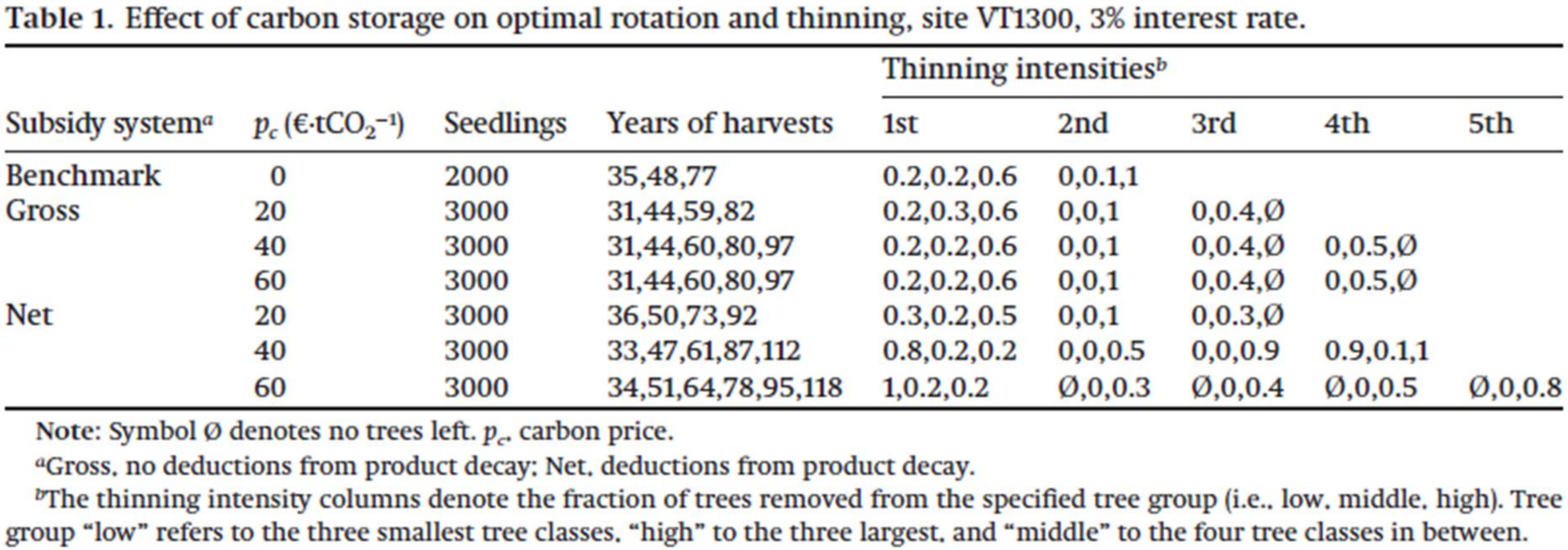


Table 1. Effect of carbon storage on optimal rotation and thinning, site VT1300, 3% interest rate.

				Thinning intensities[b]				
Subsidy system[a]	p_c (€·tCO_2^{-1})	Seedlings	Years of harvests	1st	2nd	3rd	4th	5th
Benchmark	0	2000	35,48,77	0.2,0.2,0.6	0,0.1,1			
Gross	20	3000	31,44,59,82	0.2,0.3,0.6	0,0,1	0,0.4,Ø		
	40	3000	31,44,60,80,97	0.2,0.2,0.6	0,0,1	0,0.4,Ø	0,0.5,Ø	
	60	3000	31,44,60,80,97	0.2,0.2,0.6	0,0,1	0,0.4,Ø	0,0.5,Ø	
Net	20	3000	36,50,73,92	0.3,0.2,0.5	0,0,1	0,0.3,Ø		
	40	3000	33,47,61,87,112	0.8,0.2,0.2	0,0,0.5	0,0,0.9	0.9,0.1,1	
	60	3000	34,51,64,78,95,118	1,0.2,0.2	Ø,0,0.3	Ø,0,0.4	Ø,0,0.5	Ø,0,0.8

Note: Symbol Ø denotes no trees left. p_c, carbon price.

[a] Gross, no deductions from product decay; Net, deductions from product decay.

[b] The thinning intensity columns denote the fraction of trees removed from the specified tree group (i.e., low, middle, high). Tree group "low" refers to the three smallest tree classes, "high" to the three largest, and "middle" to the four tree classes in between.

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

Rotation lengthens less with gross subsidy system.

At low CO_2 prices all thinnings are from above.
At high CO_2 prices the first thinning is from below and the rest are from above.

Source:

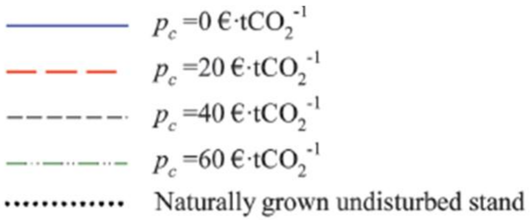
The economics of timber and bioenergy production and carbon storage in Scots pine stands

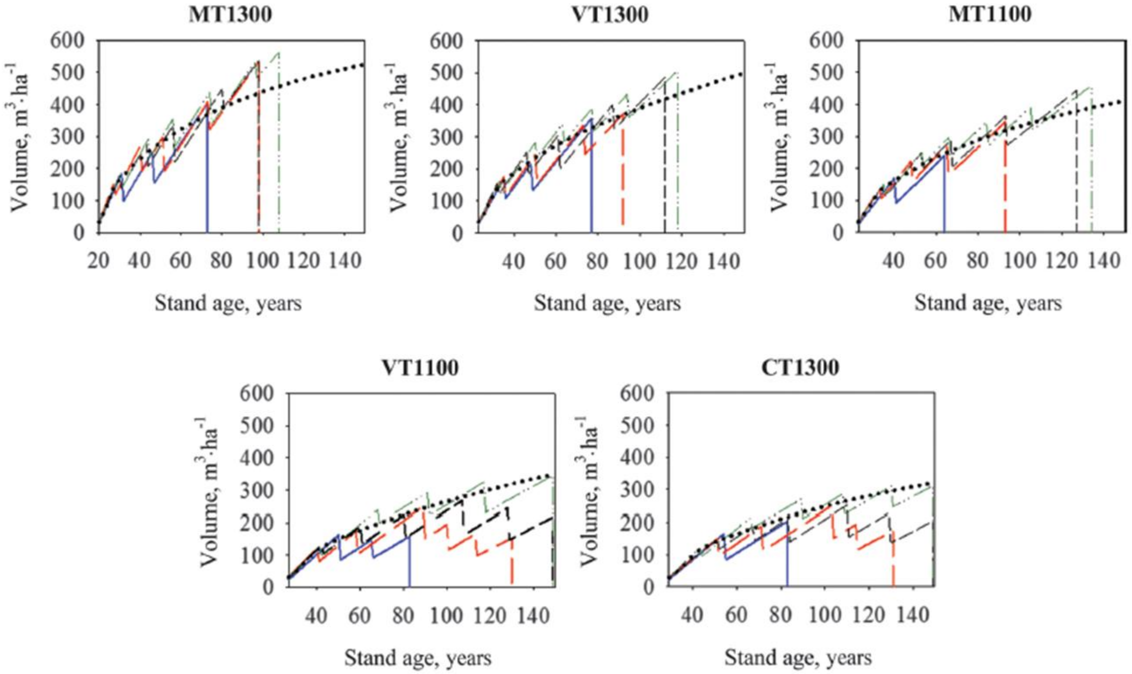
Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki

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

Timber volume

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

At good sites the optimal thinnings are light compared to the stand volume,
the volume of the stand at clearcut tends to increase with CO$_2$ price,
the stand volume increases towards the clearcut, and
the merchantable timber volume can be higher than in undisturbed stand.

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

The effects of carbon pricing on timber yield and carbon storage

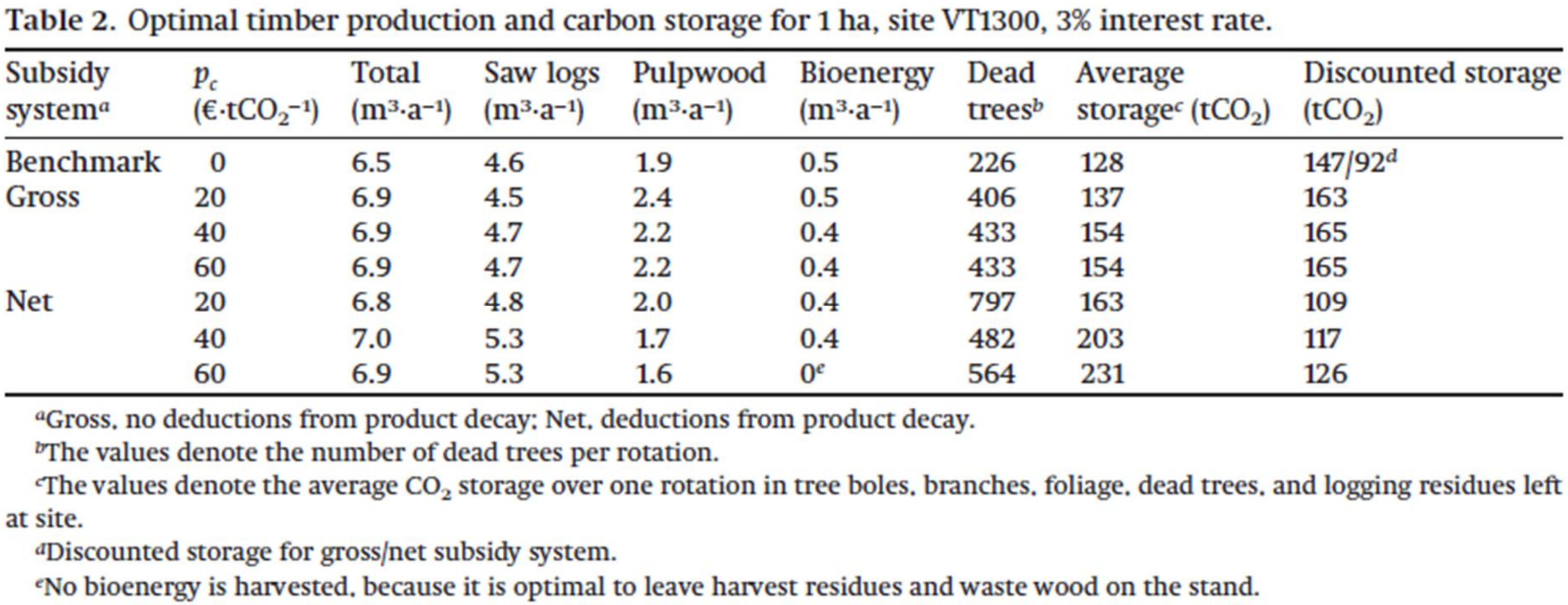


Table 2. Optimal timber production and carbon storage for 1 ha, site VT1300, 3% interest rate.

Subsidy system[a]	p_c (€·tCO_2^{-1})	Total ($m^3 \cdot a^{-1}$)	Saw logs ($m^3 \cdot a^{-1}$)	Pulpwood ($m^3 \cdot a^{-1}$)	Bioenergy ($m^3 \cdot a^{-1}$)	Dead trees[b]	Average storage[c] (tCO_2)	Discounted storage (tCO_2)
Benchmark	0	6.5	4.6	1.9	0.5	226	128	147/92[d]
Gross	20	6.9	4.5	2.4	0.5	406	137	163
	40	6.9	4.7	2.2	0.4	433	154	165
	60	6.9	4.7	2.2	0.4	433	154	165
Net	20	6.8	4.8	2.0	0.4	797	163	109
	40	7.0	5.3	1.7	0.4	482	203	117
	60	6.9	5.3	1.6	0[e]	564	231	126

[a] Gross, no deductions from product decay; Net, deductions from product decay.

[b] The values denote the number of dead trees per rotation.

[c] The values denote the average CO_2 storage over one rotation in tree boles, branches, foliage, dead trees, and logging residues left at site.

[d] Discounted storage for gross/net subsidy system.

[e] No bioenergy is harvested, because it is optimal to leave harvest residues and waste wood on the stand.

Average and discounted CO_2 storage, MAI, saw log production and mortality increase with CO_2 price.

Net subsidy: pulp production decreases with CO_2 price.
Gross subsidy system: pulp production increases with CO_2 price.

Source:

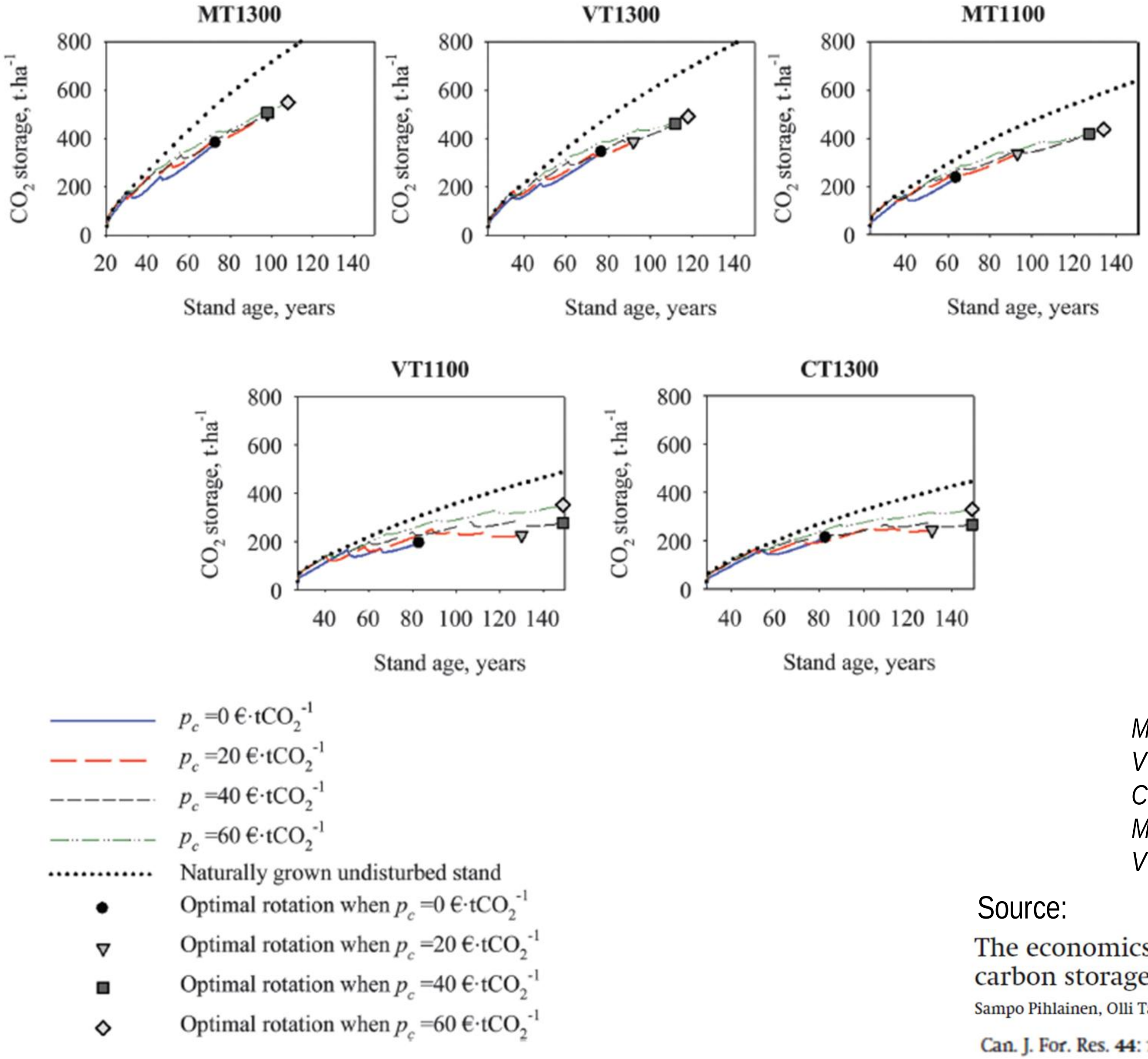
The economics of timber and bioenergy production and carbon storage in Scots pine stands

Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki

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

Total carbon storage

Fig. 3. Total carbon storage at stand and in timber products. Net subsidy system, interest rate 3%. (This figure is available in colour online.) Note: At site MT1300, the optimal rotation is 98 years at carbon prices (p_c) of €20·tCO$_2^{-1}$ and €40·tCO$_2^{-1}$.



Total carbon storage at stand and in timber products increases with CO$_2$ price.

Carbon storage is the greatest if the stands were left undisturbed.

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

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

The effects of carbon pricing in stands with different productivities

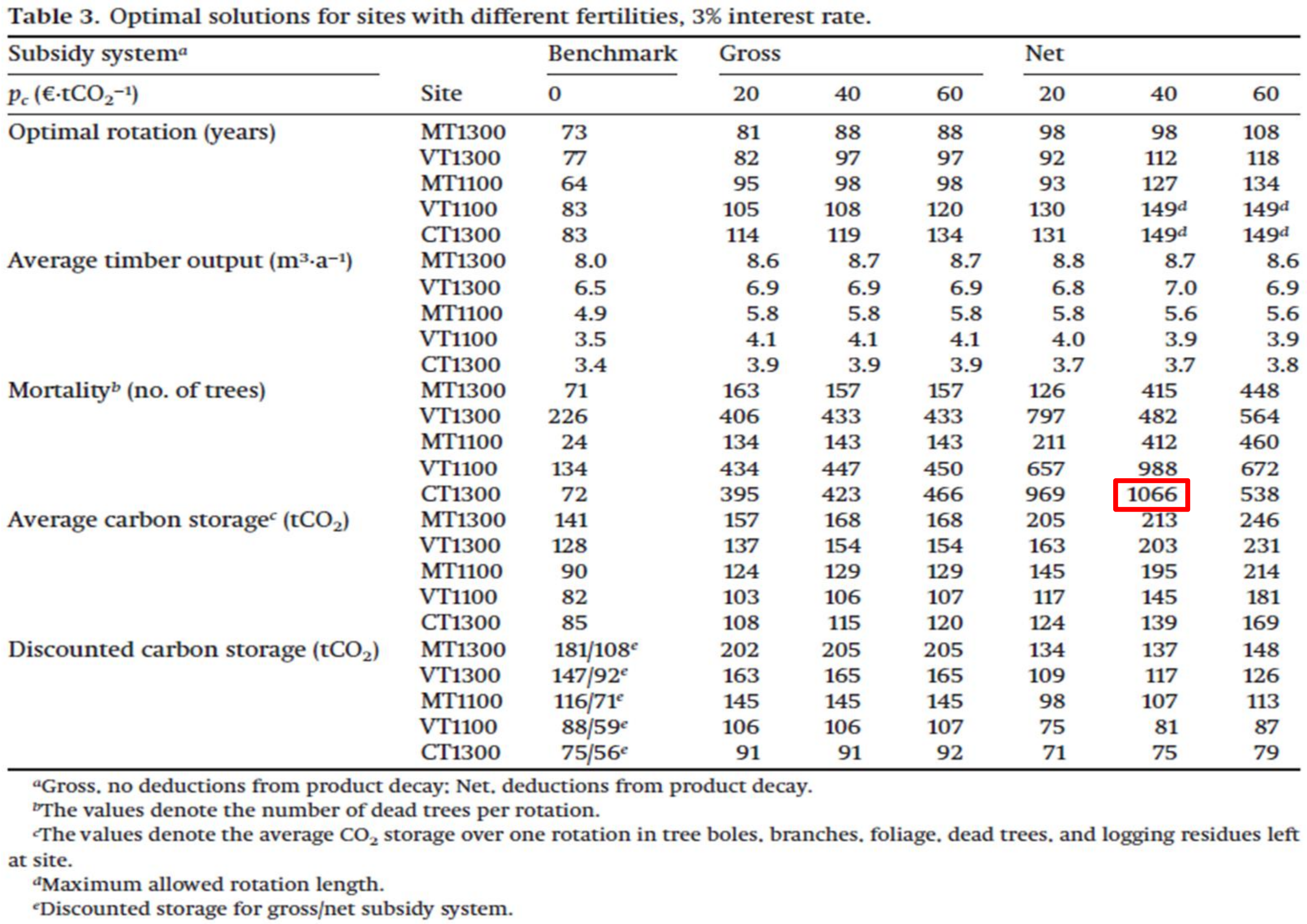


Table 3. Optimal solutions for sites with different fertilities, 3% interest rate.

Subsidy system[a]		Benchmark	Gross			Net		
p_c (€·tCO$_2^{-1}$)	Site	0	20	40	60	20	40	60
Optimal rotation (years)	MT1300	73	81	88	88	98	98	108
	VT1300	77	82	97	97	92	112	118
	MT1100	64	95	98	98	93	127	134
	VT1100	83	105	108	120	130	149[d]	149[d]
	CT1300	83	114	119	134	131	149[d]	149[d]
Average timber output (m^3·a^{-1})	MT1300	8.0	8.6	8.7	8.7	8.8	8.7	8.6
	VT1300	6.5	6.9	6.9	6.9	6.8	7.0	6.9
	MT1100	4.9	5.8	5.8	5.8	5.8	5.6	5.6
	VT1100	3.5	4.1	4.1	4.1	4.0	3.9	3.9
	CT1300	3.4	3.9	3.9	3.9	3.7	3.7	3.8
Mortality[b] (no. of trees)	MT1300	71	163	157	157	126	415	448
	VT1300	226	406	433	433	797	482	564
	MT1100	24	134	143	143	211	412	460
	VT1100	134	434	447	450	657	988	672
	CT1300	72	395	423	466	969	1066	538
Average carbon storage[c] (tCO$_2$)	MT1300	141	157	168	168	205	213	246
	VT1300	128	137	154	154	163	203	231
	MT1100	90	124	129	129	145	195	214
	VT1100	82	103	106	107	117	145	181
	CT1300	85	108	115	120	124	139	169
Discounted carbon storage (tCO$_2$)	MT1300	181/108[e]	202	205	205	134	137	148
	VT1300	147/92[e]	163	165	165	109	117	126
	MT1100	116/71[e]	145	145	145	98	107	113
	VT1100	88/59[e]	106	106	107	75	81	87
	CT1300	75/56[e]	91	91	92	71	75	79

[a] Gross, no deductions from product decay; Net, deductions from product decay.

[b] The values denote the number of dead trees per rotation.

[c] The values denote the average CO$_2$ storage over one rotation in tree boles, branches, foliage, dead trees, and logging residues left at site.

[d] Maximum allowed rotation length.

[e] Discounted storage for gross/net subsidy system.

Poor sites are more sensitive to increasing CO$_2$ price.

Effects of carbon storage greater under net subsidy

Mortality can be remarkably high at poor sites.

Source:

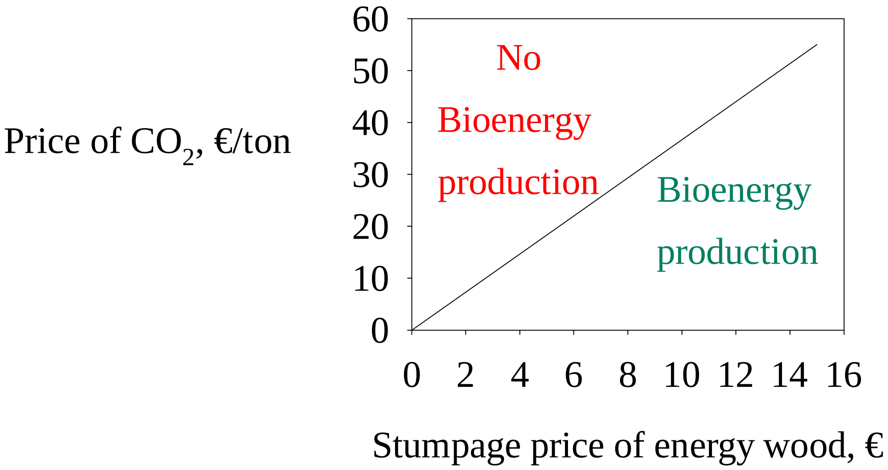
The economics of timber and bioenergy production and carbon storage in Scots pine stands

Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki

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

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:

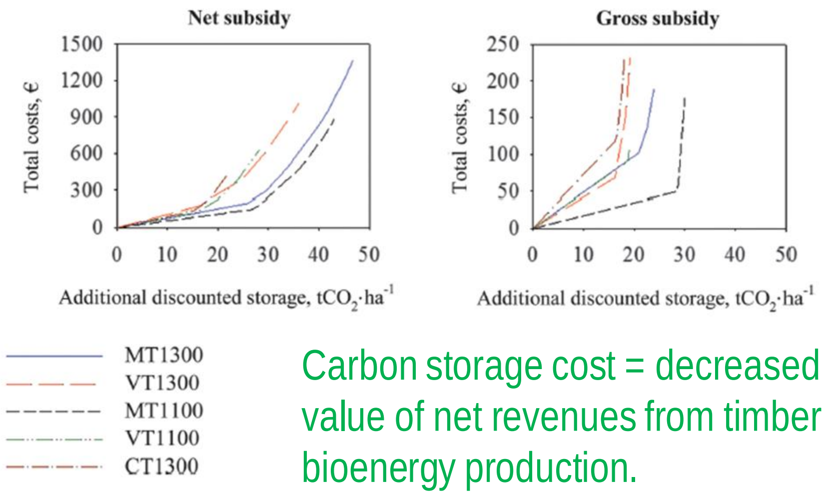
The economics of timber and bioenergy production and carbon storage in Scots pine stands

Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki

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

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

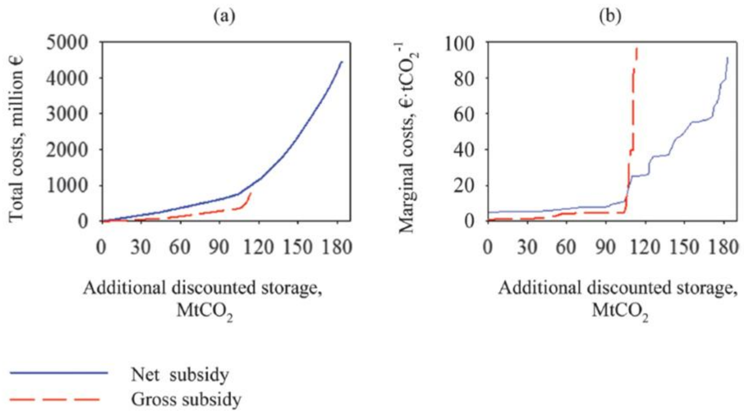
Optimization problem:

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

$$s.t.$$

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

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:

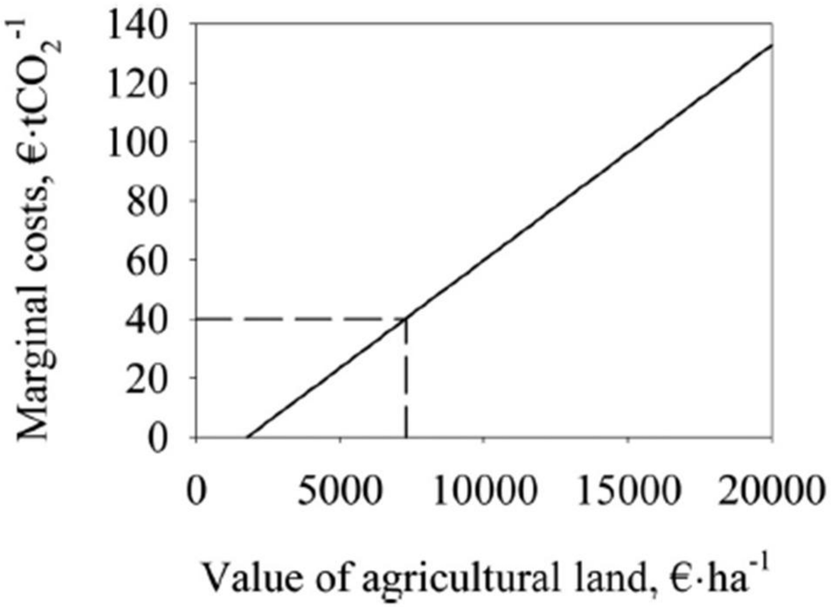
The economics of timber and bioenergy production and carbon storage in Scots pine stands

Sampo Pihlainen, Olli Tahvonen, and Sami Niinimäki

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

Optimal method for carbon storage in Finland

Fig. 7. Marginal costs of carbon storage by afforestation. Site MT1300, 3% interest rate, carbon price €40·tCO_2^{-1}, net subsidy system. The dashed line denotes that marginal costs are €40·tCO_2^{-1}, when the value of agricultural land is €7300·ha^{-1}.



It is optimal to afforest agricultural land with value less than €7300 per hectare.

Median selling price of land in 2012 was €9900–12000 per hectare in southern Finland (National Land Survey of Finland 2013)

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

Thank you!

Further information:
sampo.pihlainen@helsinki.fi