Continuous cover forestry *vs.* clearcuts with optimal carbon storage

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Carbon storage in forestry

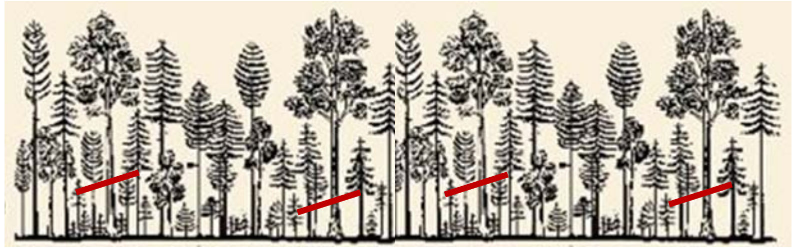
- 30 % of annual global anthropogenic CO_2 emissions absorbed by forests (FAO 2006, Pan et al. 2011)
- forest ecosystems hold > 2x the amount of carbon in the atmosphere (FAO 2006)

→ huge economic externality

Forest management regimes

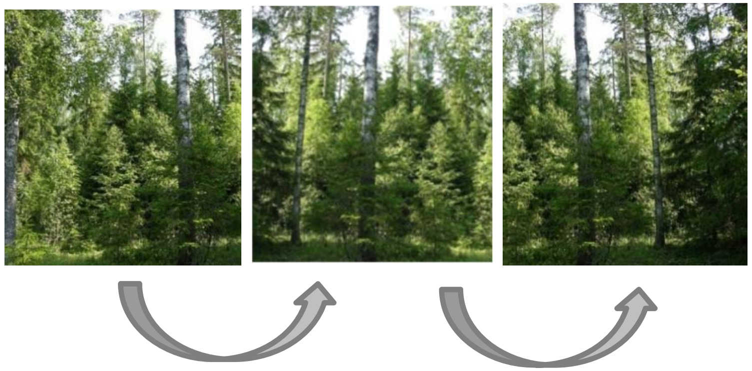
clearcut regime

(”even-aged forestry”)



continuous cover regime

(”uneven-aged forestry”, ”selection cuttings”)



Previous research on the economics of carbon storage in forestry

- Even-aged / clearcut forestry
  - van Kooten et al. (1995), Hoen & Solberg (1997), …
  - Niinimäki et al. (2013), Pihlainen et al. (2014)
- Uneven-aged / continuous cover forestry
  - Goetz et al. (2010)
  - Pukkala et al. (2011)
  - Buongiorno et al. (2012)
  - Parajuli & Chang (2012)

static "investment-efficient" approach

- Clearcuts vs. continuous cover forestry?

Contribution

- Dynamic optimization of continuous cover forestry with carbon storage in boreal context
- How does subsidized carbon storage impact the optimal choice between clearcuts and continuous cover forestry?

A model for optimal thinning and rotation (clearcut or continuous cover management)

Based on Tahvonen (2015):

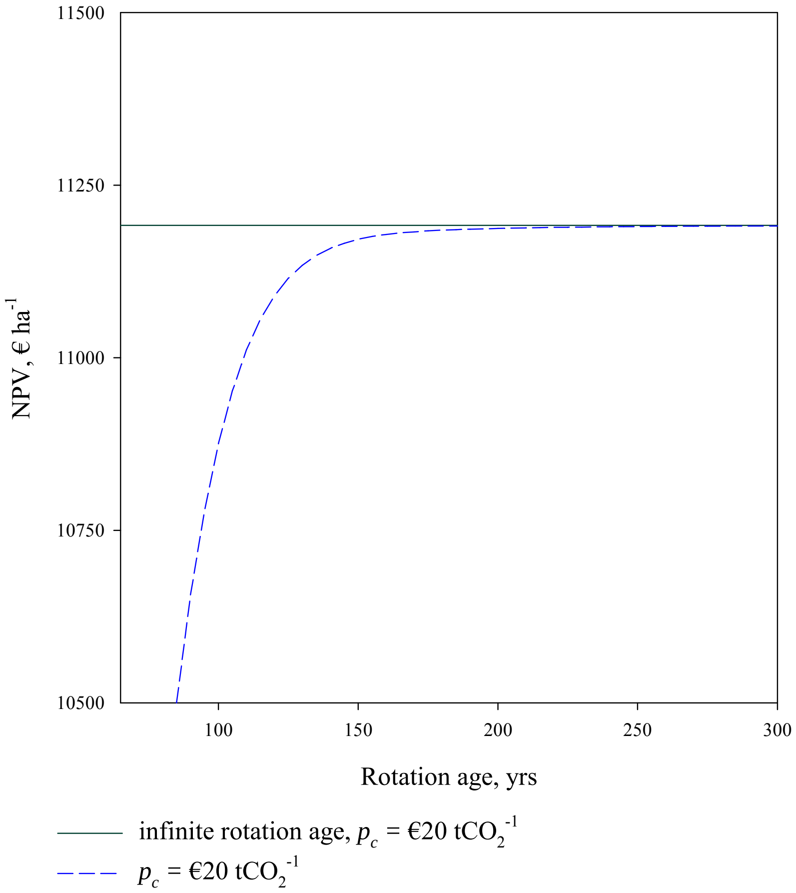
$$\max_{h_{st},T} NPV = \frac{\overset{\text{regeneration cost}}{\downarrow \atop -w} + \overbrace{\sum_{t=t_0}^{T-1} R_t b^{\Delta(t+1)}}^{\text{thinning revenues}} + \overbrace{\rho R_T b^{\Delta(T+1)}}^{\text{clearcut revenues}}}{1-b^{\Delta(T+1)}}$$

s.t. (1), (2), (3), (4), (5)

- discount factor: $b = 1/(1+\delta)$
- timber income at t : $R_t = \sum_{s=1}^{n} \left(p_{saw} v_{saw,s} + p_{pulp} v_{pulp,s} \right) h_{st}$
- planting delay t_0, rotation age T
- cost of artificial regeneration w, clearcut price premium ρ

Optimization strategy

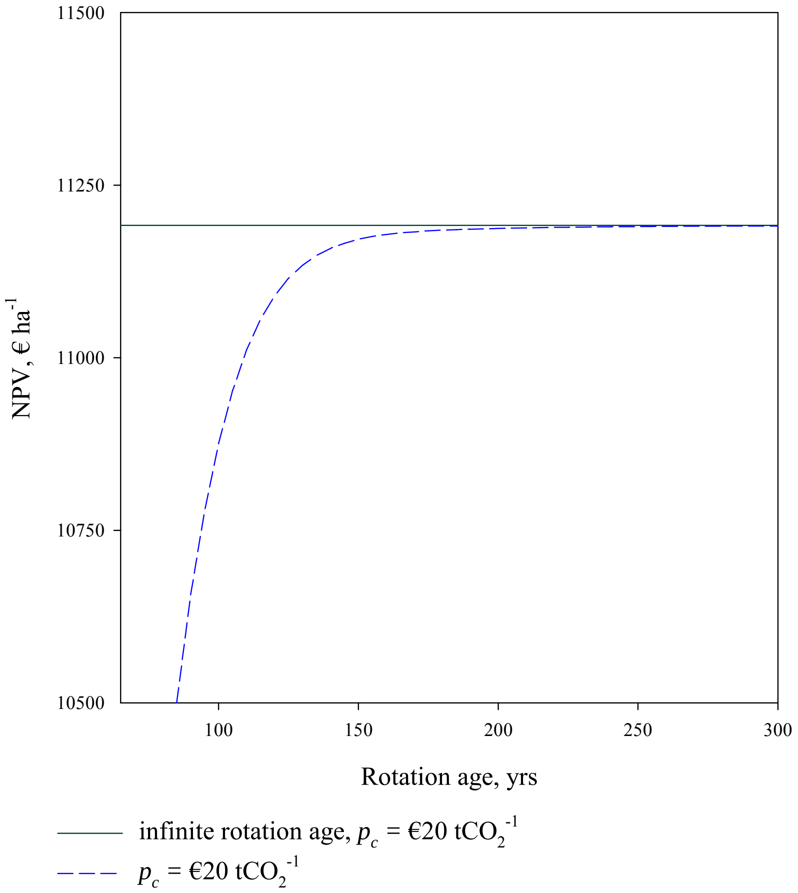
- optimize thinning h_{st} for each given rotation age T
- given optimized thinning, optimize the rotation age T
  - finite rotation → clearcutting
  - infinite rotation → continuous cover forestry



Dependence of objective value on rotation age.
Note: $\delta = 0.02$, w = €1000 ha^{-1}, SI = 15.

Optimization strategy

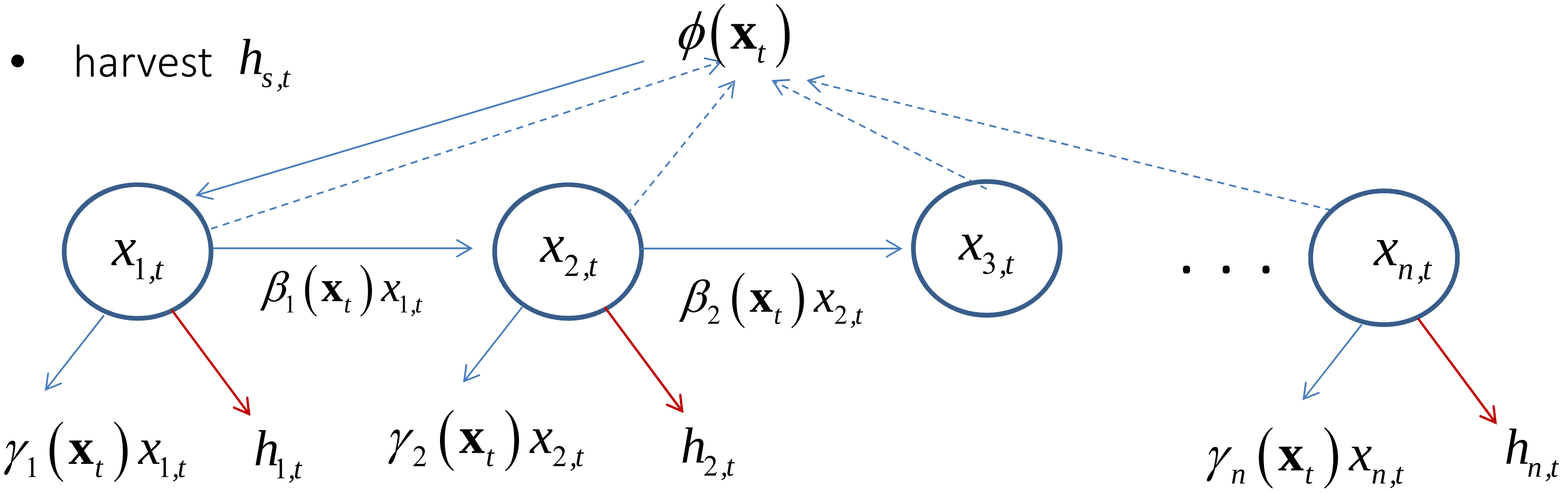
- optimize thinning h_{st} for each given rotation age T
- given optimized thinning, optimize the rotation age T
  - finite rotation → clearcutting
  - infinite rotation → continuous cover forestry
- solved using Karush-Kuhn-Tucker theorem of non-linear programming , with Knitro optimization software version 9.1
  - gradient-based interior point algorithms
  - Knitro, pattern search with Knitro (bilevel)



Dependence of objective value on rotation age.
Note: $\delta = 0.02$, w = €1000 ha^{-1}, SI = 15.

Ecological model:
discrete time transition matrix model

- a forest stand includes **trees of different size classes**
- size-class specific
  - transition to next size class $\beta_s(\mathbf{x}_t)$
  - mortality $\gamma_s(\mathbf{x}_t)$
- ingrowth $\phi(\mathbf{x}_t)$
- harvest $h_{s,t}$



Ecological model: discrete time transition matrix model

$$x_{1,t+1} = \phi\left(x_t\right) + \left[1 - \beta_1\left(x_t\right) - \gamma_1\left(x_t\right)\right] x_{1t} - h_{1t}, \quad t = t_0, ..., T, \tag{1}$$

$$x_{s+1,t+1} = \beta_s\left(\mathbf{x}_t\right) x_{st} + \left[1 - \beta_{s+1}\left(\mathbf{x}_t\right) - \gamma_{s+1}\left(\mathbf{x}_t\right)\right] x_{s+1,t} - h_{s+1,t}, \; s = 1, 2, ..., \mathrm{n} - 2, \quad t = t_0, ..., T \tag{2}$$

$$x_{n,t+1} = \beta_{n-1}\left(\mathbf{x}_t\right) x_{n-1,t} + \left[1 - \gamma_n\left(\mathbf{x}_t\right)\right] x_{nt} - h_{nt}, \quad t = t_0, ..., T \tag{3}$$

$$h_{st} \geq 0, \quad x_{st} \geq 0, \quad s = 1, 2, \ldots, n, \quad t = t_0, \ldots, T \tag{4}$$

$$x_{s,0} \quad \text{given} \tag{5}$$

Ecological model: empirical specification

Bollandsås et al. (2008)

- Norwegian growth estimations
- size-class specific
  - transition to next size class

$$\beta_{st} = \left(1.2498 + 0.0476 d_s - 11.585 \cdot 10^{-5} d_s^{\,2} - 0.3412 \Lambda_{st} + 0.906 \cdot SI - 0.024 B_t\right) / 50$$

  - mortality $\gamma_{st} = \left(1 + e^{-\left(-2.492 - 0.020 d_s + 3.2 \cdot 10^{-5} d_s^{\,2} + 0.031 \mathrm{B}_t\right)}\right)^{-1}$
- ingrowth $\phi_t = \dfrac{54.563\left(B_t + a\right)^{-0.157} \cdot SI^{0.368}}{1 + e^{\left(0.391 + 0.018 B_t - 0.066 \cdot SI\right)}}$
- site types: poor, average and high productivity site

Adding carbon subsidies to the model

Pihlainen et al. (2014):

carbon subsidy according to stand growth and carbon release from wood products

$$Q_t = \underset{\text{carbon price * CO}_2\text{ content / m}^3}{p_c\mu}\left\{\overset{\text{stand volume}}{\omega_{t+1}} - \omega_t + \underbrace{\left[1-\alpha_m(\delta)\right]m_t}_{\text{mortality volume net of decay}} + \overbrace{\left[1-\alpha_{saw}(\delta)\right]y_{saw,t}}^{\text{harvested sawtimber volume net of decay}} + \underbrace{\left[1-\alpha_{pulp}(\delta)\right]y_{pulp,t}}_{\text{harvested pulpwood volume net of decay}}\right\}$$

Optimization problem:

$$\max_{h_{st},T} NPV = \frac{-w + Q_0 b^{\Delta t_0} + \sum_{t=t_0}^{T-1}(R_t + Q_t)b^{\Delta(t+1)} + \rho R_T b^{\Delta(T+1)} + Q_T b^{\Delta(T+1)}}{1-b^{\Delta(T+1)}}$$

s.t. (1), (2), (3), (4), (5)

Main results

Optimal thinning and rotation

Interest rate	Carbon price (€ tCO_2^{-1})	Optimal rotation (years)	Mean annual sawtimber / total yield ($m^3\ ha^{-1}\ a^{-1}$)	NPV (€ ha^{-1})
0.01	0	145	6.1 / 7.1	26098
0.01	20	155	6.1 / 7.1	29680
0.01	40	165	6.2 / 7.1	33357
0.01	60	175	6.2 / 7.1	37120
0.02	0	175	5.5 / 6.6	8827
0.02	20	∞	5.4 / 5.9	11192
0.02	40	∞	5.4 / 5.9	13653
0.02	60	∞	5.5 / 5.9	16170
0.03	0	∞	4.3 / 5.0	3813
0.03	20	∞	4.3 / 5.0	5308
0.03	40	∞	5.4 / 5.9	6957
0.03	60	∞	5.4 / 5.9	8666
Undisturbed stand				
*0.01	20	∞	0	3546
Maximized discounted carbon sequestration over the infinite time horizon				
0.01	20	∞	3.2 / 3.2	15436

Optimal thinning and rotation, interest rate 2%

Interest rate	Carbon price (€ tCO_2^{-1})	Optimal rotation (years)	Mean annual sawtimber / total yield (m^3 ha^{-1} a^{-1})	NPV (€ ha^{-1})
0.02	0	175	5.5 / 6.6	8827
0.02	20	∞	5.4 / 5.9	11192
0.02	40	∞	5.4 / 5.9	13653
0.02	60	∞	5.5 / 5.9	16170
Undisturbed stand				
0.01	20	∞	0	3546

Table 2. Optimal solutions for different interest rates and carbon prices, under a product adjusted net subsidy system and site type SI=15.

Interest rate	Carbon price	Optimal rotation (years)	Thinned size classes	Mean annual sawlog / total yield	Discounted timber income	Discounted carbon subsidies	NPV	Mean CO_2 storage in stand	Mean CO_2 storage in products	Discounted CO_2 sequestration
	(€ $tCO2^{-1}$)		(starting from year)	(m^3 ha^{-1} a^{-1})	(€ ha^{-1})	(€ ha^{-1})	(€ ha^{-1})	(tCO_2 ha^{-1})	(tCO_2 ha^{-1})	(tCO_2 ha^{-1})
MSY	n/a	115	5 (40) → 6 (60)	6.0 / 7.3	n/a	n/a	n/a	118.3	155	n/a
0.01	0	145	5 (40) → 6 (90)	6.1 / 7.1	27407	0	26098	113.4	155.2	177
0.01	20	155	5 (40) → 6 (80)	6.1 / 7.1	27321	3632	29680	120.2	156.7	182
0.01	40	165	5 (40) → 6 (75) → 7 (150)	6.2 / 7.1	27151	7446	33357	126.5	157.4	186
0.01	60	175	5 (40) → 6 (65) → 7 (140)	6.2 / 7.1	26902	11431	37120	133.2	157.9	191
0.02	0	175	4 (40) → 5 (40) → 6 (145)	5.5 / 6.6	9859	0	8827	89.3	141.7	114
0.02	20	∞	5 (40) → 6 (105)	5.4 / 5.9	9760	2431	11192	101.3	135.8	122
0.02	40	∞	5 (40) → 6 (90)	5.4 / 5.9	9672	4981	13653	101.3	135.8	125
0.02	60	∞	5 (40) → 6 (80) & 7 (185)	5.5 / 5.9	9536	7634	16170	112.3	138.6	127
0.03	0	∞	4 (35) → 5 (65)	4.3 / 5.0	4813	0	3813	60.4	110.4	71
0.03	20	∞	4 (35) → 5 (40)	4.3 / 5.0	4726	1582	5308	60.4	110.4	79
0.03	40	∞	5 (40) → 6 (115)	5.4 / 5.9	4566	3390	6957	101.3	135.9	85
0.03	60	∞	5 (40) → 6 (95)	5.4 / 5.9	4499	5167	8666	101.3	135.9	86
Rule out all harvesting										
0.01	20	∞	-	0 / 0	0	4546	3546	305.6	0	227
Maximize discounted carbon sequestration over the infinite time horizon										
0.01	20	∞	7 (50) → 8 (75) → 9 (110) → 10 (155)	3.2 / 3.2	11804	4633	15436	249.5	81.3	232

Optimal stand development, interest rate 2%

Interest rate	Carbon price (€ tCO_2^{-1})	Optimal rotation (years)
0.02	0	175
0.02	20	∞
0.02	40	∞
0.02	60	∞

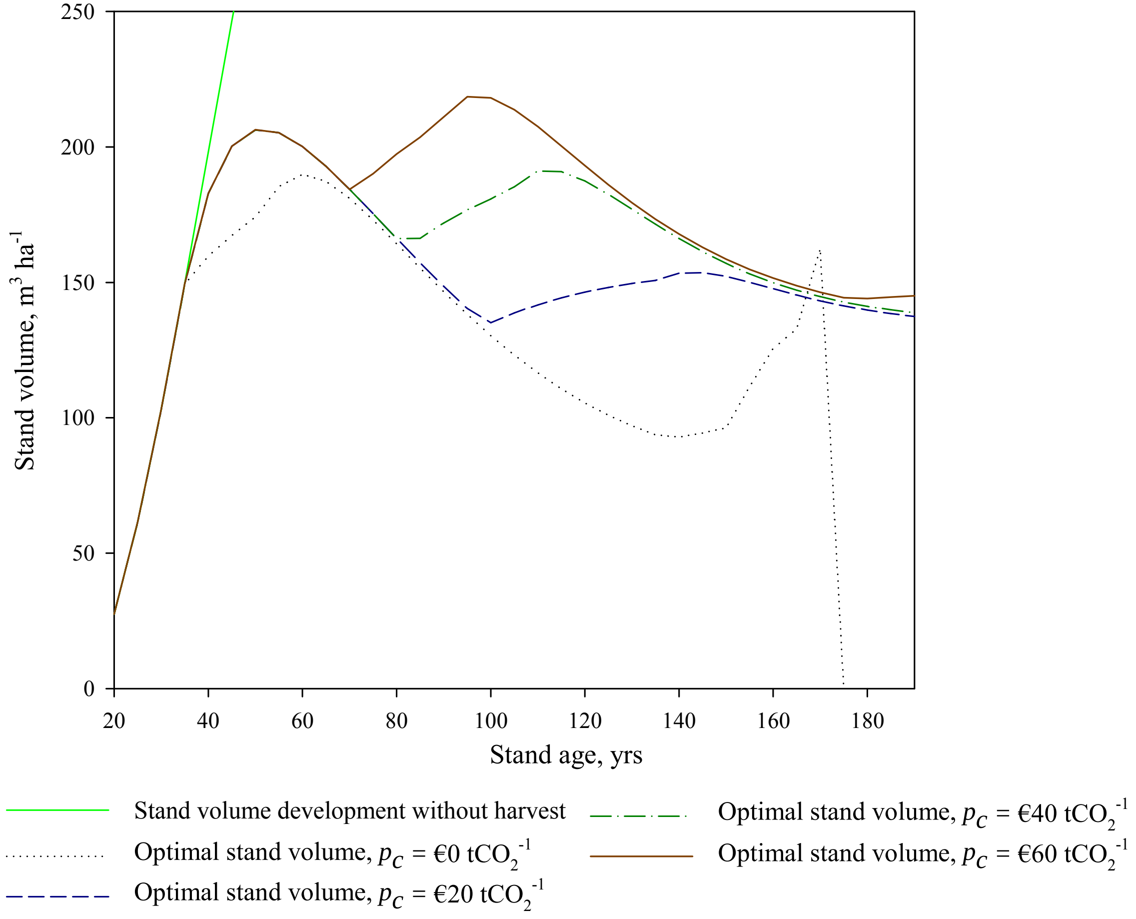
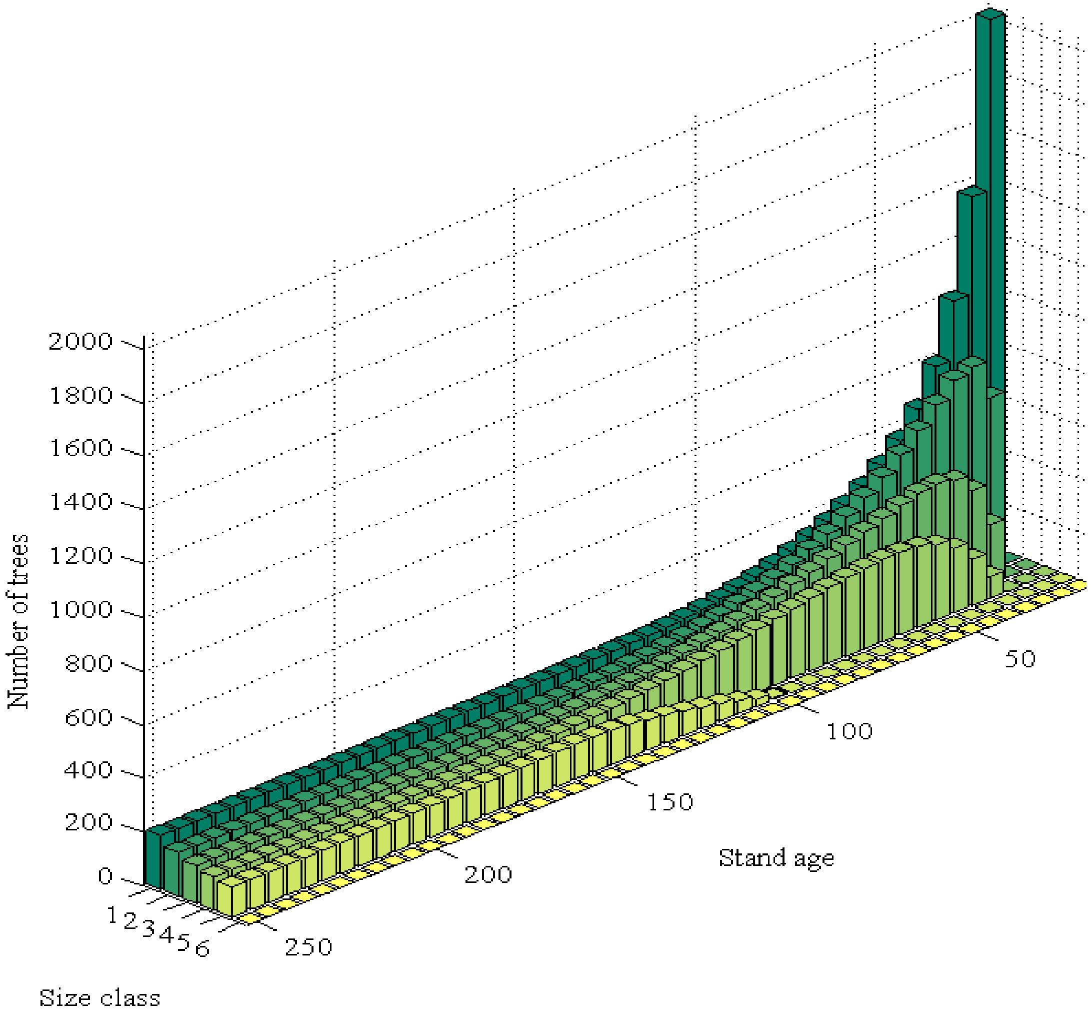


Figure 9. Stand volume development with and without harvesting.
Note: product adjusted net subsidy system, $\delta = 0.02$, w = €1000 ha^{-1}, $SI = 15$.

Optimal stand structure development, interest rate 2%

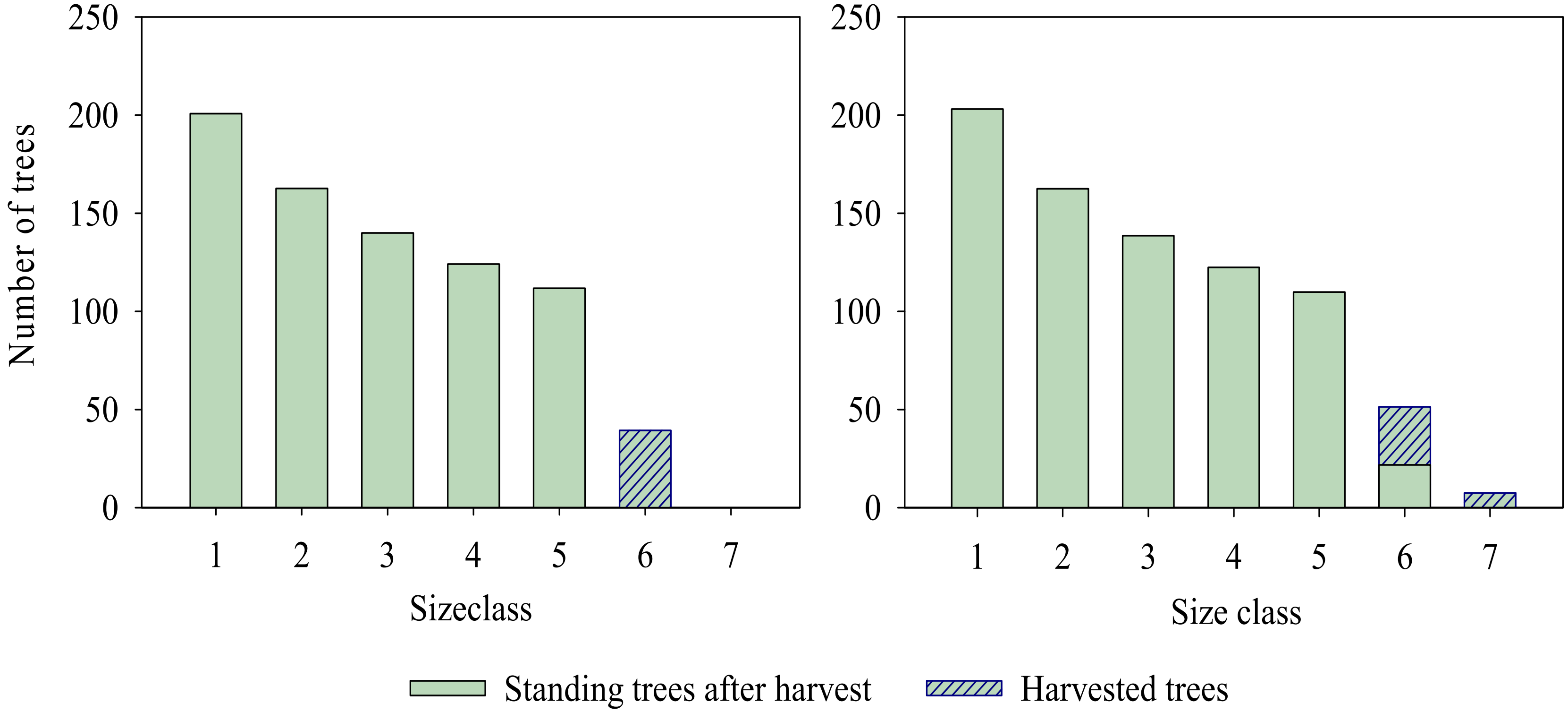


Carbon price €20 tCO_2^{-1}

→ continuous cover regime

Size class	Diameter, cm
1	7.5
2	12.5
3	17.5
4	22.5
5	27.5
6	32.5
7	37.5
8	42.5

Optimal steady state stand structure and harvest, interest rate 2%



Carbon price €20 tCO_2^{-1}
→ continuous cover optimal

Carbon price €60 tCO_2^{-1}
→ continuous cover optimal

Break-even:
Continuous cover forestry *vs.* clearcuts

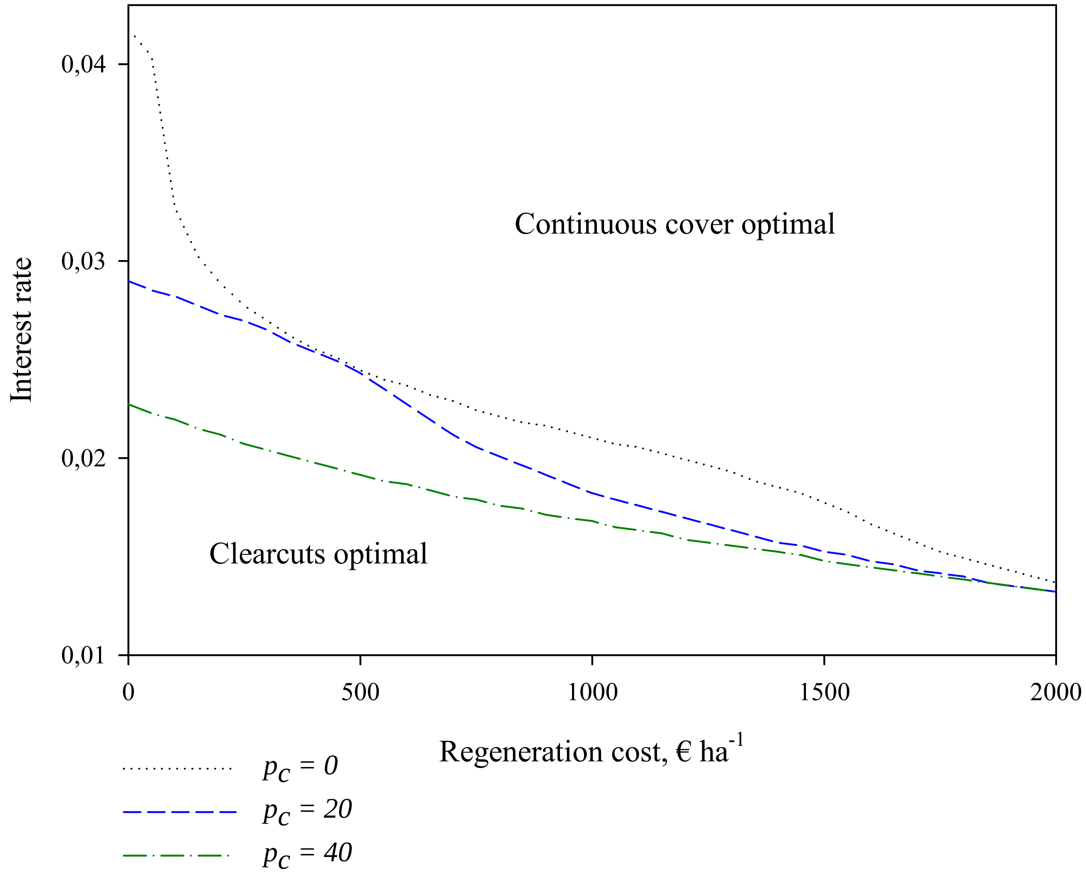


Figure 13. The optimality of continuous cover forestry vs. clearcuts under product adjusted net subsidies. Note: *SI = 15.*

Optimal carbon storage, interest rate 2%

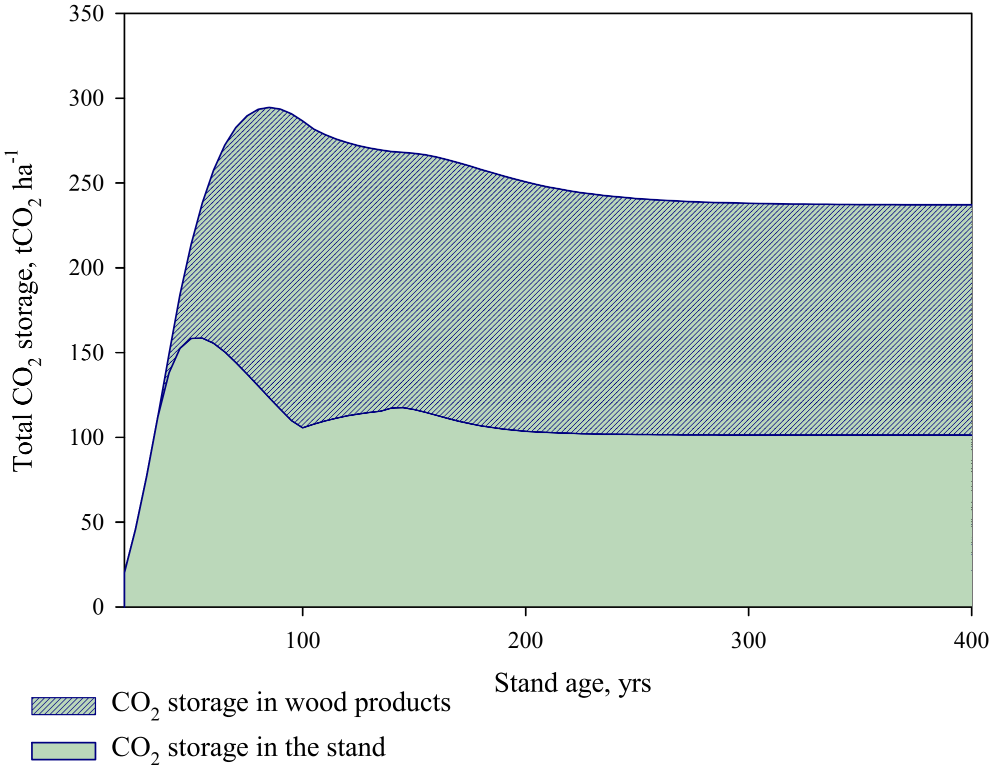


Figure 15. Carbon storage in the stand and in wood products with a carbon price of ducts,
€20 tCO_2^{-1} under product adjusted net subsidies. Note: *$\delta = 0.02$, w = 1000, SI = 15.*

Carbon price €20 tCO_2^{-1}

→ continuous cover regime

Optimal carbon storage

Interest rate	Carbon price (€ tCO_2^{-1})	Optimal rotation (years)	Mean annual sawtimber / total yield (m^3 ha^{-1} a^{-1})	Mean CO_2 storage in **stand** (tCO_2 ha^{-1}) +	Mean CO_2 storage in **products** (tCO_2 ha^{-1}) =	**Total** CO_2 storage (tCO_2 ha^{-1})
0.01	0	145	6.1 / 7.1	113	155	269
0.01	20	155	6.1 / 7.1	120	157	277
0.01	40	165	6.2 / 7.1	127	157	284
0.01	60	175	6.2 / 7.1	133	158	291
0.02	0	175	5.5 / 6.6	89	142	231
0.02	20	∞	5.4 / 5.9	101	136	237
0.02	40	∞	5.4 / 5.9	101	136	237
0.02	60	∞	5.5 / 5.9	112	139	251
0.03	0	∞	4.3 / 5.0	60	110	171
0.03	20	∞	4.3 / 5.0	60	110	171
0.03	40	∞	5.4 / 5.9	101	136	237
0.03	60	∞	5.4 / 5.9	101	136	237
No harvesting		∞	0	306	0	306
Maximize discounted carbon sequestration over the infinite time horizon						
0.01	20	∞	3.2 / 3.2	250	81	331

Effect of site type

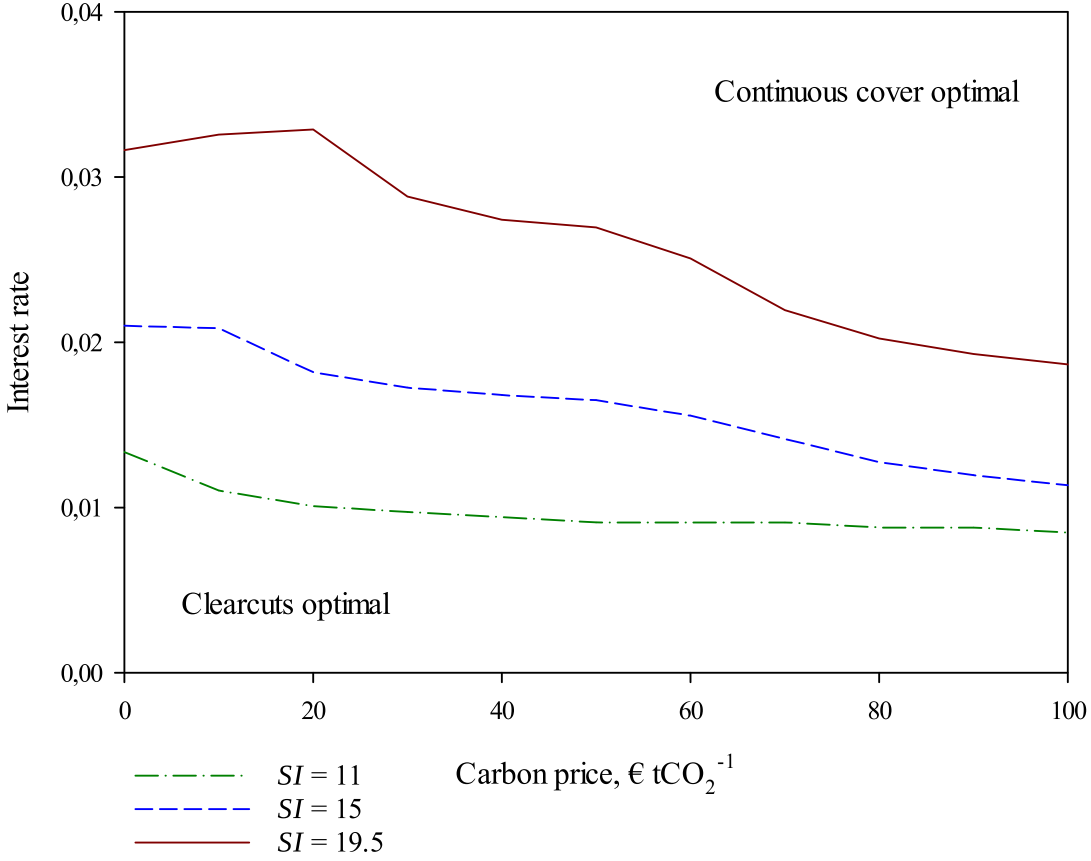


Figure 18. The optimality of continuous cover forestry vs. clearcuts under a product adjusted net subsidy system. Note: w = €1000 ha^{-1}.

Concluding remarks

- carbon subsidization increases stand volume and CO_2 storage, as in Goetz et al. (2010), Niinimäki et al. (2013) and Pihlainen et al. (2014)
- thinning from above → yield predominantly sawtimber

→ importance of CO_2 storage in products

- carbon subsidies improve the competivity of continuous cover management relative to clearcuts
- changes in various economic and ecological parameters may bring about management regime shifts

Thank you!

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