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1 Economics of size-structured forestry with carbon storage

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14 *Abstract*

15

16 We study the economics of carbon storage using a model that includes forest size structure and
17 determines the choice between rotation forestry and continuous cover forestry. Optimal harvests may
18 rely solely on thinning, implying infinite rotation and continuous cover forestry, or both thinning and
19 clearcuts, implying finite rotation periods. Given several carbon prices and interest rates, we optimize
20 the timing and intensity of thinnings along with the choice of management regime. In addition to the
21 carbon storage in living trees, we include the carbon dynamics of dead trees and timber products.
22 Forest growth is specified by an empirically validated transition matrix model for Norway spruce
23 (*Picea abies* (L.) Karst.). The optimization problem is solved in its general dynamic form by applying
24 bilevel optimization with gradient-based interior point methods and a genetic algorithm. Carbon
25 pricing postpones thinnings, increases stand density by directing harvests to larger trees, and typically
26 yields a regime shift from rotation forestry to continuous cover forestry. In continuous cover
27 solutions, the steady-state harvesting interval and the diameter distribution of standing and harvested
28 trees are sensitive to carbon price, implying that carbon pricing increases the sawlog ratio of timber
29 yields. Additionally, we obtain relatively inexpensive stand-level marginal costs of carbon storage.

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36 Keywords: carbon sequestration, carbon subsidy, continuous cover forestry, management regimes,
37 optimal rotation, uneven-aged forestry

38

39 1. Introduction

40 Holding more than double the amount of carbon in the atmosphere, forest ecosystems are a crucial
41 part of the global carbon cycle (FAO 2006). Carbon storage in forests can be maintained and increased
42 by reducing deforestation, by afforestation and by changing stand-level forest management practices
43 (IPCC 2014). While increasing forest cover may be challenging due to competing land uses
44 (Lubowski et al. 2006), enhancing carbon storage per hectare of existing forestland may be a cost-
45 efficient mitigation option. Our study analyses economically optimal carbon storage in size-structured
46 stands of Norway spruce (*Picea abies* (L.) Karst.). Unlike previous studies, we apply a forest
47 economic model that encompasses the two alternative forest management regimes: forest
48 management based on clearcuts and management that maintains forest cover continuously. Using this
49 generalized model, we present a detailed analysis of the effects of carbon storage on optimal
50 management practices, including the choice between management regimes. The latter is vital given
51 that climate change adaptation and biodiversity protection may motivate a more widespread
52 application of continuous cover management (Gauthier et al. 2015).

53 In the boreal region and beyond, forestry has relied heavily on the rotation regime, where forest
54 stands are artificially regenerated and finally clearcut, resulting in more or less even-aged stands
55 (Gauthier et al. 2009). However, planted even-aged forests account for only 13% of managed forest
56 area globally (FAO 2010, Payn et al. 2015). Further, recent research suggests that plantation forestry
57 may be more vulnerable to disturbances related to climate change than forest management that
58 maintains structurally diverse stands (Gauthier et al. 2015). An alternative to the rotation regime is
59 continuous cover or uneven-aged forestry, where the stand is managed by partial cuttings (i.e.
60 thinnings). Regeneration occurs naturally, resulting in a heterogeneous age and size distribution. In
61 comparison to rotation forestry, continuous cover forestry is likely to support more biodiversity and
62 other ecosystem services (Calladine et al. 2015, O'Hara 2014) and to be more resilient against threats
63 brought about by climate change (Thompson et al. 2009).

64 While continuous cover forestry shows promise for climate change adaptation, cost-efficient
65 mitigation measures have been analysed almost exclusively in the framework of rotation forestry. A
66 seminal paper by van Kooten et al. (1995) examines the effect of carbon pricing on optimal rotation
67 age and supply of carbon services. Akao (2011) shows how the effects of carbon storage on optimal
68 rotation age depend on assumptions concerning the carbon release from wood products, while Hoel
69 et al. (2014) extend the van Kooten et al. (1995) framework by including forests' multiple carbon
70 pools, harvest residues and the use of timber for bioenergy. These along with numerous other studies
71 apply the generic version of the Faustmann optimal rotation model, where stands can be harvested
72 solely by clearcutting (Samuelson 1976). As commercial thinnings have an important role in e.g.
73 Nordic context, they have been incorporated into even-aged models with carbon storage by e.g.
74 Huang and Kronrad (2006), Pohjola and Valsta (2007) and Daigneault et al. (2010). Further,
75 Niinimäki et al. (2013) for Norway spruce and Pihlainen et al. (2014) for Scots pine highlight the
76 importance of adapting thinning strategies (in addition to the rotation period) for economically
77 optimal carbon storage.

78 Studies on optimal carbon storage in continuous cover forestry are scarce, and most of the
79 existing contributions have limited their scope to steady states (e.g. Buongiorno et al. 2012). Goetz
80 et al. (2010) is an exception, as they dynamically optimize timber production and carbon storage in
81 uneven-aged stands of Scots pine in Spain. The question of the relative profitability of rotation vs.
82 continuous cover forestry in the co-production of timber and carbon storage has been touched upon
83 in certain studies: Gutrich and Howarth (2007) compare management regimes with carbon storage,
84 but do not optimize the regime choice, while Pukkala et al. (2011) analyse the choice of management
85 regime applying a model without sound economic basis. As far as we know, no studies exist using a
86 detailed dynamic model for analysing the effect of carbon storage on the choice between these two
87 management regimes.

88 This gap is not surprising, as up to very recently, the economics of even- and uneven-aged
89 forestry have been analysed separately and with divergent models. While the literature on even-aged
90 forestry builds on Faustmann (1849), the first attempts to optimize uneven-aged management include
91 de Liocourt (1898) and Adams and Ek (1974). As discussed in Getz and Haight (1989, p. 287–295)
92 and Rämö and Tahvonen (2014), many studies have attempted to bypass the dynamic complexities
93 involved in optimizing uneven-aged forestry. However, seminal contributions by Haight (1985) and
94 Haight and Getz (1987) correctly specify the uneven-aged problem as an infinite time horizon
95 problem without *ad hoc* restrictions. Recently it has been shown that when the optimal choice
96 between continuous cover *vs.* rotation forestry is determined endogenously, both management
97 regimes can be analysed using the same model (Tahvonen and Rämö 2016). This generalized
98 approach allows for the optimization of stand management – thinnings and the (potentially infinite)
99 rotation age – over an infinite time horizon given any initial state. The study at hand extends this
100 model by including the social value of carbon storage.

101 Our present study is the first one to apply an empirically validated size-structured growth model
102 to the problem of optimal carbon storage with endogenous choice of management regime. Our study
103 features a detailed economic setup with empirically estimated variable harvesting cost functions,
104 along with fixed harvesting costs that necessitate the optimization of thinning intervals. This not only
105 allows us to obtain the first results on optimal harvest timing in uneven-aged forestry with carbon
106 storage, but is also essential for accurately determining the relative economic performance of the
107 rotation and continuous cover regimes. The effect of carbon storage on the optimal choice between
108 these regimes is a question with major practical implications, but one that has not been satisfactorily
109 studied in the previous literature. Our carbon storage formulation explicitly includes carbon dynamics
110 in the whole tree biomass, in dead tree matter and in timber products with distinct decay rates for
111 sawlog and pulpwood products. By combining detailed economic and ecological models, and by

112 optimizing not only rotation age but thinnings and the management regime as well, we are able to
 113 determine the most cost-efficient methods for enhancing carbon storage in managed forests.

114 We continue by introducing the growth model and the optimization problem. Thereafter we
 115 present the empirical parameter values and the computational methods. This is followed by results on
 116 optimal stand management, on timber production and carbon storage, and on forestry revenues and
 117 carbon storage costs. Finally, we discuss our results by comparing them with earlier studies and draw
 118 conclusions.

119 2. The growth model and the optimization problem

120 We denote the number of trees in size class s at the beginning of period t by
 121 x_{st} , $s = 1, 2, \dots, n$, $t = t_1, t_1 + 1, \dots, T + 1$. Accordingly, the stand state at period t can be given as
 122 $\mathbf{x}_t = [x_{1t}, x_{2t}, \dots, x_{nt}]$. Let us denote the fraction of trees moving to size class $s + 1$ at period t by
 123 $\beta_s(\mathbf{x}_t)$, $s = 1, 2, \dots, n$, where $\beta_n(\mathbf{x}_t) \equiv 0$. The natural mortality in size class s at period t is
 124 $\mu_s(\mathbf{x}_t)$, $s = 1, 2, \dots, n$. Thus the fraction of trees remaining in the same size class equals
 125 $1 - \beta_s(\mathbf{x}_t) - \mu_s(\mathbf{x}_t)$, $s = 1, 2, \dots, n$. Natural regeneration is described by ingrowth, i.e. trees entering
 126 the smallest size class. Ingrowth at the beginning of period t is denoted by $\phi(\mathbf{x}_t)$. Additionally, we
 127 denote the number of trees harvested from size class s at the end of period t by
 128 h_{st} , $s = 1, 2, \dots, n$, $t = t_1, t_1 + 1, \dots, T$. Hence, stand development can be described by the difference
 129 equations

$$130 \quad (1) \quad x_{1,t+1} = \phi(\mathbf{x}_t) + [1 - \beta_1(\mathbf{x}_t) - \mu_1(\mathbf{x}_t)]x_{1t} - h_{1t},$$

$$131 \quad (2) \quad x_{s+1,t+1} = \beta_s(\mathbf{x}_t)x_{st} + [1 - \beta_{s+1}(\mathbf{x}_t) - \mu_{s+1}(\mathbf{x}_t)]x_{s+1,t} - h_{s+1,t}, \quad s = 1, 2, \dots, n-2,$$

$$132 \quad (3) \quad x_{n,t+1} = \beta_{n-1}(\mathbf{x}_t)x_{n-1,t} + [1 - \mu_n(\mathbf{x}_t)]x_{nt} - h_{nt},$$

133 where $t = t_1, t_1 + 1, \dots, T$.

134 We assume that the stand is artificially regenerated after a clearcut, and the time interval
 135 between the regeneration activities and the ingrowth of trees into the smallest size class equals a
 136 certain number of periods denoted by t_1 . Thus, t_1 periods after planting, we have an initial stand
 137 composed of a given number of trees in size class 1. The stand is clearcut if the rotation length
 138 $T \in [t_1, \infty)$ is finite.

139 Let $w \geq 0$ (€ ha⁻¹) denote the cost of artificial regeneration. We denote the discount factor by
 140 $b = 1/(1+r)$, where r refers to the annual interest rate. The length (in years) of a period is denoted by
 141 Δ . Revenues, $R(\mathbf{h}_t)$ from thinning and $R(\mathbf{x}_T)$ from clearcuts, depend on the number and size of
 142 trees harvested. The revenues per period are specified as

$$143 \quad (4) \quad R(\mathbf{h}_t) = \sum_{s=1}^n h_{st} (v_{\sigma,s} p_{\sigma} + v_{\varpi,s} p_{\varpi}), \quad t = t_1, t_1 + 1, \dots, T,$$

144 where $v_{\sigma,s}$ and $v_{\varpi,s}$ are the sawlog and pulpwood volumes in a tree of size class s , and p_{σ} and p_{ϖ}
 145 are the respective (roadside) prices (€ m⁻³). Variable harvesting costs (for cutting and hauling) are
 146 given separately for thinning and clearcuts by $C_i(\mathbf{h}_t)$, $i = th, cl$. A fixed harvesting cost denoted by
 147 C_f covers e.g. the transportation of machinery to the stand site. Because of the fixed cost it may not
 148 be optimal to harvest the stand in every period. This is taken into account by the binary variables
 149 $\delta_t \in \{0,1\}$, $t = t_1, t_1 + 1, \dots, T$ and by the Boolean operator $h_t = \delta_t h_t$. When the choice is $\delta_t = 1$, the
 150 levels of $h_{st} \geq 0$, $s = 1, 2, \dots, n$ can be freely optimized. When $\delta_t = 0$, the only admissible choice is
 151 $h_{st} = 0$, $s = 1, 2, \dots, n$.

152 As carbon storage in forests is a positive externality, we assume a Pigouvian subsidy system
 153 resembling the one in van Kooten et al. (1995). Accordingly, society pays the forest owner for the
 154 amount of CO₂ that is absorbed as the stand grows, and charges for the amount of CO₂ that is released
 155 as a consequence of harvesting and natural mortality. Let $p_c \geq 0$ (€ tCO₂⁻¹) denote the economic

156 value of CO₂. We let $\omega_t = \sum_{s=1}^n x_{s,t} (v_{\sigma,s} + v_{\varpi,s})$ denote the merchantable timber volume (i.e. stem
 157 volume) of the stand at the beginning of period t . Density factor ρ converts stem volume into stem
 158 dry mass. In addition to the stem, trees are comprised of non-merchantable matter, i.e. foliage,
 159 branches, bark, stumps and roots. Expansion factor η converts stem dry mass into whole tree dry
 160 mass. Hence, the total tree biomass in the stand at the beginning of period t can be given as
 161 $B_t(\mathbf{x}_t) = \rho\eta\omega_t$, and net biomass growth in period t as $B_{t+1}(\mathbf{x}_{t+1}) - B_t(\mathbf{x}_t)$. The amount of CO₂ in one
 162 dry mass unit equals θ .

163 We denote the dry mass of sawlog and pulpwood harvested at the end of period t by
 164 $y_{\sigma,t} = \rho \sum_{s=1}^n h_{st} v_{\sigma,s}$ and $y_{\varpi,t} = \rho \sum_{s=1}^n h_{st} v_{\varpi,s}$, respectively. Logging will not instantly release the
 165 carbon content of timber into the atmosphere because it is only gradually released from timber
 166 products as they decay (Liski et al. 2001). Dead tree matter is created both through natural mortality
 167 and from harvest residues (i.e. non-merchantable parts of the harvested trees) left in the forest. The
 168 dry mass of dead tree matter formed through natural mortality in period t equals
 169 $d_{m,t} = \rho\eta \sum_{s=1}^n \mu(\mathbf{x}_t)_{s,t} x_{s,t} (v_{\sigma,s} + v_{\varpi,s})$. Further, the dry mass of harvest residues created at the end of
 170 period t can be given as $d_{h,t} = (\eta - 1)(y_{\sigma,t} + y_{\varpi,t})$. We denote the annual decay rates of sawlog,
 171 pulpwood and dead tree matter, respectively, by g_j ($j = \sigma, \varpi, d$). The urgency of mitigating climate
 172 change implies that society is likely to have a positive time preference for net emissions. It can be
 173 shown that, per unit of wood product or dead tree matter, the present value of future emissions due to
 174 decay equals $p_c \alpha_j(r)$, where

$$175 \quad (5) \quad \alpha_j(r) = \frac{g_j}{g_j + r}$$

176 (cf. Pihlainen et al. 2014, Assmuth and Tahvonen 2017).

177 Thus the economic value of net carbon sequestration (or net negative emissions) in period t can
 178 be given as

$$179 \quad (6) \quad Q_t = p_c \theta \{ B_{t+1}(\mathbf{x}_{t+1}) - B_t(\mathbf{x}_t) + [1 - \alpha_\sigma(r)] y_{\sigma,t}(\mathbf{h}_t) + [1 - \alpha_\varpi(r)] y_{\varpi,t}(\mathbf{h}_t) + [1 - \alpha_d(r)] (d_{m,t}(\mathbf{x}_t) + d_{h,t}(\mathbf{h}_t)) \}$$

180 for $t = t_1, t_1 + 1, \dots, T$,

181 where $B_{t+1}(\mathbf{x}_{t+1}) - B_t(\mathbf{x}_t)$ refers to net growth, i.e. the change in biomass net of harvests. The
 182 additional elements $[1 - \alpha_\sigma(r)] y_{\sigma,t}(\mathbf{h}_t)$ and $[1 - \alpha_\varpi(r)] y_{\varpi,t}(\mathbf{h}_t)$ are needed to take into account
 183 that harvested trees are used for sawlog and pulpwood products, respectively, which release their
 184 carbon content as they decay. Correspondingly, $[1 - \alpha_d(r)] (d_{m,t}(\mathbf{x}_t) + d_{h,t}(\mathbf{h}_t))$ refers to dead tree
 185 matter (from natural mortality and harvest residue) and its decay.

186 The problem of optimizing harvests over an infinite horizon can now be given as

$$187 \quad (7) \quad J(\mathbf{x}_0, T) = \max_{\{h_{st}, \delta_t, T \in [t_1, \infty)\}} \frac{-w + \sum_{t=0}^T Q(\mathbf{x}_t, \mathbf{h}_t) b^{\Delta(t+1)} + \sum_{t=t_1}^T [R(\mathbf{h}_t) - C_i(\mathbf{h}_t) - \delta_t C_f] b^{\Delta(t+1)}}{1 - b^{\Delta(T+1)}}$$

188 s.t. (1) – (3) and

$$189 \quad (8) \quad \delta_t \in \{0, 1\}, \quad t = t_1, t_1 + 1, \dots, T$$

$$190 \quad (9) \quad x_{st} \geq 0, \quad s = 1, 2, \dots, n, \quad t = t_1, t_1 + 1, \dots, T + 1,$$

$$191 \quad (10) \quad h_{st} = \delta_t h_{st} \geq 0, \quad s = 1, 2, \dots, n, \quad t = t_1, t_1 + 1, \dots, T,$$

$$192 \quad (11) \quad \mathbf{x}_{T+1} = 0,$$

$$193 \quad (12) \quad x_{s,t_1} \text{ given.}$$

194 The optimal forest management regime is determined by the choice of T . If – given optimized
 195 thinnings – the objective functional is maximized by a finite rotation age, rotation forestry is optimal.
 196 If no maximum exists and the bare land value converges toward the continuous cover forestry bare
 197 land value from below as $T \rightarrow \infty$, then it is optimal to apply continuous cover management.

198 3. Ecological and economic parameter values

199 We apply an empirical growth model by Bollandsås et al. (2008) for Norway spruce at latitude 61.9
 200 °N. The model has been estimated using the National Forest Inventory of Norway, and includes
 201 functions for ingrowth, mortality and diameter increment. We study an average productivity site ($SI = 15$), implying that the height of the dominant trees at the age of 40 (100) years is 15 (24) metres.
 202 We use 12 size classes with diameters (midpoints) ranging from 7.5 cm to 62.5 cm with 5.0 cm
 203 intervals. Table 1 presents the size class -specific parameter values (Rämö and Tahvonen 2014). The
 204 length of a period (Δ) is five years and the time interval from planting to the emergence of trees into
 205 the first size class is 20 years (i.e. $t_1 = 4$). The initial stand structure is given as $\mathbf{x} = [2250, 0, 0, \dots]$,
 206 i.e. 20 years after artificial regeneration, 2250 trees emerge in the smallest size class.

208 The estimated natural mortality during the 5-year period t in size class s is given as

$$209 \mu_{st} = \left(1 + e^{-(-2.492 - 0.020M_s + 3.2 \cdot 10^{-5}M_s^2 + 0.031A_t)} \right)^{-1}, \text{ where } M_s \text{ is the diameter (midpoint) of size class}$$

210 s and A_t the total stand basal area ($\text{m}^2 \text{ ha}^{-1}$) at the beginning of period t . The fraction of trees
 211 moving to the next size class during period t is denoted by

$$212 \beta_{st} = (1.2498 + 0.0476M_s - 11.585 \cdot 10^{-5}M_s^2 - 0.3412L_{st} + 0.906 \cdot SI - 0.024A_t) / 50,$$

213 where L_{st} is the total basal area of size classes $s+1, \dots, n$ at the beginning of period t . The estimated
 214 number of trees entering the smallest size class (i.e. natural regeneration) during the 5-year period t

$$215 \text{ is given as } \phi_t = \frac{54.563(A_t + a)^{-0.157} \cdot SI^{0.368}}{1 + e^{(0.391 + 0.018A_t - 0.066 \cdot SI)}}.$$

216 Note that ϕ is strictly convex in $\mathbf{x}$, implying nonconvexities in the optimization problem. In
 217 Bollandsås et al. (2008), $a = 0$ and $\phi \rightarrow \infty$ as $\mathbf{x} \rightarrow 0$. This feature is unwarranted, and based on
 218 Wikberg (2004) and Pukkala et al. (2009) we set $a = 0.741$, which implies $\phi(0) = 100$. This

219 correction parameter decreases the ingrowth by less than one tree per year when basal area is above
 220 2 m².

221 The roadside prices for sawtimber and pulpwood are €58.44 m⁻³ and €34.07 m⁻³, respectively.
 222 The fixed harvesting cost equals €500 ha⁻¹. For the variable harvesting costs we use empirically
 223 estimated functions by Nurminen et al. (2006), based on the performance of modern harvesters. The
 224 variable harvesting costs (cutting and hauling) depend on the number and volumes of trees cut, and
 225 are given separately for thinning and clearcuts as

$$226 \quad C_i = C_{i0} C_{i1} \sum_{s=1}^n h_{st} \left(C_{i2} + C_{i3} v_s - C_{i4} v_s^2 \right) + C_{i5} \left[C_{i6} \sum_{s=1}^n h_{st} v_s + C_{i7} \left(\sum_{s=1}^n h_{st} v_s \right)^{0.7} \right], i = th, cl.$$

227 C_{i0} is the per-minute cutting cost (€), and its coefficient $C_{i1}(\bullet)$ is the time (in minutes) spent cutting
 228 one tree and moving the machinery to the next tree. C_{i5} and its coefficient $[\bullet]$ are the cost and time
 229 spent in hauling, respectively, while $v_s = v_{\sigma,s} + v_{\varpi,s}$ is the volume of a tree in size class s . The
 230 parameter values for C_{ik} , $i = th, cl$, $k = 0, \dots, 7$ are given in Table 2. The parameter $C_{th1} = 1.150$ in the
 231 cutting cost element for thinning takes into account that cutting one tree and moving to the next one
 232 is more costly in (continuous cover) thinning compared to clearcuts (Surakka and Siren 2007).
 233 Additionally, hauling is more time-consuming in thinnings than in clearcuts. The cost of artificial
 234 regeneration is €1000–1500 ha⁻¹ (Niinimäki et al. 2012). We apply the lower bound because this will
 235 reveal how carbon storage alters the choice between continuous cover and rotation forestry.

236 Based on Lehtonen et al. (2004), the stemwood density factor (ρ) for Norway spruce is 0.3774
 237 tonnes of dry matter per cubic metre of fresh volume, and the expansion factor to convert stem dry
 238 mass into whole tree dry mass (η) equals 2.1566. Following Niinimäki et al. 2013, the CO₂ content
 239 of a wood dry mass unit (θ) is obtained by multiplying the share of carbon in biomass dry weight
 240 (0.5) with the coefficient that converts tonnes of carbon to tonnes of CO₂ (44/12). Thus we set
 241 $\theta = 1.83333 \text{ tCO}_2 \text{ t}^{-1}$. For the decay rate of dead tree matter we use $g_d = 0.18196$ based on the average

242 rate of stem, foliage, branches, bark, stumps and roots in Hyvönen and Ågren (2001). To obtain the
243 decay rates for sawlog and pulpwood products we use data presented in Liski et al. (2001) on the
244 division of sawlog and pulpwood removals for production lines, on production losses, and on the
245 division into timber product types with different lifespans. The obtained parameter values are $g_{\sigma} =$
246 0.06611 and $g_{\sigma} = 0.47070$.

247 4. Computational methods

248 Because the harvest timing variables are integers, but harvest intensities are continuous, the task is to
249 solve a mixed-integer nonlinear programming problem. To do this, we apply bilevel optimization
250 (Colson et al. 2007).¹ The lower-level problem is computed using version 9.0 of the Knitro
251 optimization software, which applies advanced gradient-based interior point algorithms (Byrd et al.
252 2006). The maximized objective value of the lower-level problem forms the objective value given
253 any vector of harvest timing binaries. The harvest timing vector is optimized using a genetic algorithm
254 (Deb and Sinha 2010, Sinha et al. 2017). The optimal harvest schedules are solved for a series of
255 rotation lengths. If the objective function obtains a maximum with some $T \in [60, 180)$ years, the
256 optimal rotation is finite. If the value of the objective function continues to increase as the rotation
257 period is lengthened, the optimal rotation is infinite. In this case, the optimal continuous cover
258 solution is obtained by lengthening the horizon to obtain a close approximation of the infinite horizon
259 solution. To handle potential non-convexities, we apply multiple randomly chosen initial points in
260 the optimization. For the genetic algorithm, we use a randomly generated initial population of 40
261 harvest timing vectors, and for each harvest intensity optimization we use four random initial points.
262 These values were found to be sufficient for finding the same local optimum as a higher number of
263 initial guesses. Using efficient parallel computation (Intel (R) Xeon (R)E5-2643 v3 @3.40GHZ, 24

¹ A similar approach has been applied to a forest management problem without carbon storage in Tahvonen and Rämö (2016).

logical processors), the optimal harvest intensity and timing is found within 3–36 h. The solution times for the lower level problem are typically 5–15 seconds with approximately 20% variability in the objective values of the local optima based on different initial points.

5. Results

The effects of carbon pricing on optimal stand management

For reference, we first briefly state results for the generic Faustmann setting (Samuelson 1976), where harvesting can be carried out solely in clearcuts (i.e. no thinnings), and no natural regeneration takes place. This setting is similar to that of the carbon storage study by van Kooten et al. (1995). Given an annual interest rate of 2%, with zero carbon price, the optimal rotation age is 60 years. Setting a carbon price of €20 (€30) tCO_2^{-1} lengthens the optimal rotation period to 65 (70) years, while a carbon price of €60 tCO_2^{-1} implies a 90-year rotation period. Given a 4% annual interest rate, the effect of carbon pricing on rotation length is somewhat stronger. Increasing the carbon price from zero to €60 tCO_2^{-1} increases the optimal rotation age from 50 years to 110 years.

We now turn to the full economic setup with optimized intensity and timing of thinnings along with an optimized rotation period and management regime. Given a 2% annual interest rate, optimal rotation age increases with carbon price (Table 3, Figure 1). The optimal rotation length without carbon pricing equals 130 years. The relatively long rotation follows from optimally utilizing natural regeneration. When carbon price equals €10 (€20) tCO_2^{-1} , the rotation age is 150 (170) years. Given a carbon price of €30 tCO_2^{-1} or higher, the optimal rotation period is infinitely long, implying that continuous cover forestry is superior to rotation forestry. Given a 4% interest rate, the optimal rotation is infinite even with zero carbon price (Table 3, Figure 2). This is because a high interest rate makes it optimal to postpone or avoid the investment in artificial regeneration, as natural regeneration maintains a sufficient level of growth without costs. Moreover, a higher interest implies lower optimal

288 stocking and thus a smaller opportunity cost of delaying the clearcut. Additionally, the time delay
289 between stand regeneration and the first revenues from thinnings becomes costly when discounting
290 is heavier. This encourages a shift to continuous cover forestry with more frequently repeated
291 harvests.

292 Regardless of management regime (rotation forestry or continuous cover forestry), optimal
293 thinning is invariably performed from above, always fully cutting down the largest harvested size
294 class. Relative value growth is very high in small trees, implying that it is optimal to postpone
295 harvesting until they have grown to a size that yields sawlog. Given a 2% interest rate and zero carbon
296 price, the first thinning takes place 45 years after stand regeneration (Table 3, Figure 1). Carbon
297 pricing postpones the first thinning by five years, and increases mean stand volume along the rotation
298 – or, in the case of continuous cover solutions, at the steady state (Table 3). The timing and intensity
299 of subsequent thinnings can be seen in Figure 1, where stand volume and the number of trees drop
300 after each harvest. Given a 4% interest rate and no carbon pricing, the first thinning is carried out
301 already at a stand age of 40 years (Table 3, Figure 2), as it is optimal to maintain less capital in the
302 stand. A carbon price of €20 (€60) tCO_2^{-1} postpones the first thinning by five (15) years.

303 The relative effect of carbon pricing on optimal stand management and stand density is larger
304 with a higher interest rate. Given a 2% interest rate, mean stand volumes range from 138 to 224 m^3
305 ha^{-1} for carbon prices €0–€60 tCO_2^{-1} ; given a 4% interest rate the corresponding mean stand volumes
306 span from 68 to 234 $\text{m}^3 \text{ha}^{-1}$ (Table 3). From the economic point of view, forest carbon storage
307 essentially means shifting net emissions forward in time. Thus stronger discounting implies a stronger
308 incentive to adapt forest management to provide more carbon storage.

309 The higher the carbon price, the larger the harvested trees at the continuous cover steady states
310 (Table 3, Figure 3). Additionally, the number of size classes harvested equals the number of five-year
311 periods between the steady-state harvests. Given a 2% interest rate and a carbon price of €30 tCO_2^{-1} ,
312 trees are harvested from five size classes in the optimal continuous cover solution (diameter midpoints

313 32.5, 37.5, 42.5, 47.5 and 52.5 cm) with a 25-year interval. When carbon price increases to €60 tCO₂⁻¹,
314 ¹, it is optimal to forgo harvesting the 32.5 cm diameter class and to only cut trees with diameters of
315 37.5–52.5 cm. This is achieved by switching to a 20-year harvesting interval (Table 3). Thus harvest
316 timing adjusts to the carbon price to maintain optimal average stand density and economic return
317 (including carbon subsidies) along the harvest interval.

318 Given a 4% interest rate and zero carbon price, the steady-state harvest takes place every 20
319 years, and targets trees with diameters of 22.5–37.5 cm (Table 3, Figure 3). With a €10 tCO₂⁻¹ carbon
320 price, the steady-state harvesting interval equals 25 years, allowing some trees to enter the 42.5 cm
321 size class before they are harvested. Increasing the carbon price further shifts the steady-state harvests
322 to larger size classes, implying a higher mean stand volume. While the number of trees decreases
323 with tree size class (Figure 3, column a), large trees comprise a considerable fraction of the total stem
324 volume because of their high volume per tree (Figure 3, column b).

325
326 *The effects of carbon pricing on timber production and carbon storage*

327 Given a 2% interest rate and zero carbon price, mean annual sawlog yield over the rotation equals 6.3
328 m³ ha⁻¹, while mean annual total yield (sum of sawlog and pulpwood) equals 7.6 m³ ha⁻¹ (Table 4).
329 Increasing the carbon price to €10 (€20) tCO₂⁻¹ increases mean sawlog yield to 6.5 (6.7) m³ ha⁻¹ while
330 total yield remains unchanged, i.e. the sawlog-pulp ratio increases. This has a positive effect on
331 carbon storage because the typical decay rate of sawlog products is notably slower than that of
332 pulpwood. Increasing the carbon price to €30 tCO₂⁻¹ implies a regime shift from rotation forestry to
333 continuous cover forestry, and decreases mean sawlog and total yield while increasing the sawlog
334 ratio. The explanation is that continuous cover management tends to produce somewhat lower mean
335 yields than rotation forestry, even when the bare land value of the former is higher. Increasing the
336 carbon price further, to €60 tCO₂⁻¹, has only a negligible effect on mean sawlog and total yields.

337 Given a 4% interest rate and no carbon pricing, mean sawlog and total yields are low, 3.8 and
338 4.5 m³ ha⁻¹ a⁻¹, respectively (Table 4). This is due to the low optimal level of growing capital. With
339 carbon pricing, trees are allowed to grow bigger before they are harvested (Table 3), which increases
340 yields when the carbon price is relatively low. For example, given a carbon price of €30 tCO₂⁻¹, the
341 mean sawlog yield equals 5.7 m³ ha⁻¹ and mean total yield is 6.7 m³ ha⁻¹. However, with €60 tCO₂⁻¹
342 carbon price, mean sawlog and total yields equal 5.6 and 5.8 m³ ha⁻¹, respectively (Table 4). This
343 implies that when the carbon price is sufficiently high, yields begin to decrease with carbon price
344 because only very large trees are harvested.

345 Natural mortality remains rather low in economically optimal solutions, but dead tree matter is
346 generated from harvest residues. Each harvest decreases the carbon storage in living trees, but causes
347 a temporary increase in carbon storage in dead tree matter and in timber products (Figure 4). The
348 latter two, however, quickly decrease as a consequence of decay. This is especially true for clearcuts
349 (Figure 4a–c), which yield large amounts of rapidly decaying pulpwood. Because of exponential
350 decay, the initial carbon stocks in dead tree matter and in timber products reach a steady state, where
351 total carbon storage at the beginning of the rotation equals total carbon storage at the end of the
352 rotation. In continuous cover solutions (Figure 4d), carbon stocks in living trees, dead tree matter and
353 timber products go through a transition phase before reaching a steady state.

354 Mean carbon storage in living trees increases with carbon price (Table 4). For example, given
355 a 2% interest rate and no carbon pricing, the average amount of carbon stored in living trees over a
356 rotation is 207 tCO₂ ha⁻¹; increasing the carbon price to €60 tCO₂⁻¹ increases mean storage to 335
357 tCO₂ ha⁻¹. Additionally, mean carbon storage in dead tree matter and timber products generally
358 increase with carbon price. An exception is the regime shift from rotation forestry to continuous cover
359 forestry (2% interest rate, carbon price from €20 to €30 tCO₂⁻¹). As mentioned, rotation forestry
360 produces high total yields and thus large amounts of harvest residues, and average natural mortality
361 is somewhat higher in rotation forestry than in continuous cover forestry. Moreover, the calculation

362 of mean carbon storage in dead tree matter and timber products takes into account the accumulation
363 of these stocks from one rotation to the next.

364 In solutions where continuous cover management is optimal, the steady state may be reached
365 as late as approximately 300 years after stand regeneration. This implies that in terms of economic
366 outcome, the carbon storage taking place during the long transition phase towards the steady state is
367 likely to be more important than mean carbon storage. Discounted CO₂ sequestration (tCO₂ ha⁻¹) is
368 the sum of all periodic net carbon fluxes within the infinite planning horizon, each discounted to the
369 present (stand regeneration) moment. For example, given a 2% interest rate and a carbon price of €20
370 tCO₂⁻¹, the net carbon sequestration over the infinite horizon is equivalent to 232 tonnes of CO₂
371 emissions abated immediately. Discounted CO₂ sequestration increases monotonously with carbon
372 price (Table 4).

373 *Forestry revenues and the cost of carbon storage*

374 The higher the carbon price, the lower the discounted timber income (Table 5). This is true despite of
375 the fact that the mean timber yields do not monotonically decrease with carbon price (Table 4). The
376 decrease in discounted timber income is partly explained by differences in harvest timing: when
377 carbon storage is valued, harvests are carried out later. Additionally, deviating from the optimal
378 timber-only solution implies higher harvesting costs per timber unit. However, the decrease in timber
379 income is more than compensated by carbon subsidies that represent the economic value of carbon
380 storage. Including carbon storage benefits improves net present values (i.e. bare land value)
381 considerably: given a 2% (4%) interest rate, a carbon price of €20 tCO₂⁻¹ increases net present value
382 by 50% (137%) (Table 5). If the social value of carbon storage is high (€30 or €60 tCO₂⁻¹ depending
383 on interest rate), the economic benefits from carbon storage clearly outweigh the income from timber
384 production.

385 The economic cost of additional carbon storage, i.e. the cost of carbon abatement in forestry, is
386 measured as lost timber income. To obtain marginal abatement costs, we divide the incremental

387 decrease (i.e. from the solution with a lower carbon price) in timber income for each optimal solution
388 by the corresponding incremental increase in discounted CO₂ sequestration.² Marginal abatement
389 costs increase with the amount of carbon abatement (Figure 5). Given a 2% interest rate, marginal
390 costs range from €3 to €46 tCO₂⁻¹ for 10 to 70 tonnes of carbon abatement per hectare. Given a 4%
391 interest rate abatement is somewhat more costly, but carbon abatement up to 33 tonnes per hectare
392 can be achieved with a marginal cost below €40 tCO₂⁻¹.

393 6. Discussion and conclusions

394 It is widely established in the literature that valuing carbon storage increases optimal rotation age in
395 even-aged forestry (e.g. van Kooten et al. 1995, Stainback and Alavalapati 2002, Gutrich and
396 Howarth 2007, Pohjola and Valsta 2007). While our findings support this result, our model differs
397 from previously published models in many important aspects and is able to shed light on previously
398 unaddressed questions. Unlike many studies, we include thinnings, and optimize their timing along
399 with their intensity. Further, we determine the optimal management regime – rotation forestry or
400 continuous cover forestry – endogenously. As far as we know, such an optimization approach has not
401 been combined with carbon storage using a size-structured description of forest resources.

402 Including thinnings (and natural regeneration) is essential for our approach, because it implies
403 that timber revenues may be obtained from a forest that is never clearcut. This is not the case in
404 studies applying the classic Faustmann rotation model, e.g. van Kooten et al. (1995) and Hoel et al.
405 (2014). van Kooten et al. (1995) find that carbon pricing generally increases rotation ages only
406 moderately, but in certain cases might yield a result where it is optimal to forgo harvesting completely.
407 Hoel et al. (2014) show that rotation age typically increases with the social cost of carbon and may
408 become infinitely long (i.e. forestry is abandoned). According to our results, carbon pricing may
409 indeed render the optimal rotation infinitely long, but instead of total abandonment of harvesting as

² Note that an amount of discounted CO₂ sequestration corresponds to an equal amount of emissions abated immediately.

410 in van Kooten et al. (1995) and Hoel et al. (2014), it then becomes optimal to manage the stand with
411 thinnings (i.e. apply continuous cover forestry).

412 According to studies that included optimized thinnings in their even-aged setup (e.g. Pohjola
413 and Valsta 2007, Daigneault et al. 2010, Niinimäki et al. 2013), carbon pricing tends to postpone
414 thinnings, increase mean stand volume and lengthen the optimal rotation period. Our results support
415 these findings. However, our generalized model yields optimal solutions that go beyond the scope of
416 earlier studies limited to forests without natural regeneration. Given the low interest rate (2%),
417 optimal rotations are long, ranging from 130 to 170 years for carbon prices €0–€20 tCO₂⁻¹. With a
418 €30 tCO₂⁻¹ carbon price, clearcutting is suboptimal, i.e. the optimal management regime switches
419 from rotation forestry to continuous cover forestry. Given a higher interest rate (4%), continuous
420 cover forestry dominates rotation forestry regardless of carbon price³, and management adapts to
421 carbon pricing by changing the timing and targeting of thinnings.

422 In our model setup, it is possible to exclude natural regeneration by setting $\phi(\mathbf{x}_t) = 0$ in Eq. 1
423 (implying that any naturally regenerated saplings are cleared away, and the clearing is costless). If
424 this is done, we obtain optimal rotation ages that are well in line with those obtained in earlier studies
425 on even-aged Norway spruce: the study by Solberg and Haight (1991) based on a size-structured
426 growth model, and the study by Niinimäki et al. (2013) utilizing a highly detailed process-based
427 model. Without natural regeneration and given a 2% interest rate, our optimal rotation lengths range
428 from 100 to 155 years for carbon prices €0–€60 tCO₂⁻¹. Given a 4% interest rate, rotation periods for
429 carbon prices €0–€30 tCO₂⁻¹ span from 100 to 130 years, while a carbon price of €60 tCO₂⁻¹ yields an
430 optimal rotation as long as 215 years.

431 With the exception of Goetz et al. (2010), studies on uneven-aged management with carbon
432 storage tend to apply static optimization, which does not allow optimizing stand transition from any

³ This is in line with Tahvonen and Rämö (2016), where high site productivity, low interest rate and low regeneration cost favour the clearcut regime instead of continuous cover regime, and *vice versa*.

433 initial state that is not close to the steady state (e.g. Pukkala et al. 2011, Buongiorno et al. 2012).
434 Further, as far as we know, our study presents the first results on optimal harvest timing in uneven-
435 aged forestry with carbon storage. Our results suggest that when beginning with bare land, the large
436 initial cohorts are intensively utilized in a series of thinnings before approaching the steady state, and
437 that these thinnings are postponed and moderated by carbon pricing. Reaching the steady state may
438 take as much as 300 years from stand regeneration, which emphasizes the importance of the transition
439 phase for the present value of net revenues from both timber production and carbon storage. We also
440 show that the steady-state harvesting interval, along with the diameter distribution of the standing and
441 harvested trees, react to changes in carbon price. The average size of the harvested trees increases
442 with carbon price, and four (or five) diameter classes are fully harvested each 20 (25) years at the
443 steady state.

444 The carbon storage formulation presented in van Kooten et al. (1995) takes into account that
445 while carbon is stored in living trees, it may also be stored to some extent in timber products. We add
446 detail to this formulation by explicitly including carbon storage in timber products and in dead tree
447 matter. Our results suggest that a small carbon stock is maintained in dead tree matter, formed from
448 harvest residues and through natural mortality. To account for carbon storage in timber products, we
449 use distinct decay rates for sawlog and pulpwood (cf. Pihlainen et al. 2014). This is important because
450 our size-structured model enables us to direct thinnings to trees of specific size, making use of the
451 fact that large trees yield relatively more sawlog than small trees. Sawlog, in turn, is superior to
452 pulpwood in its ability to store carbon for extended periods. Such targeted harvesting is by definition
453 impossible in clearcuts, which inevitably results in the harvesting of quickly decaying pulpwood. This
454 becomes costly with a high carbon price. Hence the impact of carbon storage on the relative
455 profitability of rotation forestry vs. continuous cover forestry cannot be fully captured by a model that
456 omits the size structure of the stand, or the varying decay profiles of timber assortments. According

457 to our results, carbon pricing indeed increases the sawlog-pulp ratio of the mean annual yield and
458 may induce a regime shift to continuous cover forestry.

459 The model developed in this study is a stand-level model, and thus does not include market
460 interactions. However, our results yield some initial understanding on the effects of carbon storage
461 on wood supply. In general, carbon pricing increases mean total annual yields, mostly due to
462 increased sawlog production. The only exception to this is the case with a low interest rate (2%),
463 where a carbon price of €30 tCO₂⁻¹ induces a shift from rotation forestry to continuous cover
464 management with somewhat lower mean yields. Given an interest rate equal or above 4%, continuous
465 cover management with fairly low stand density is optimal when carbon storage is not valued, and
466 carbon pricing clearly increases stocking levels along with the yields.

467 The cost of artificial regeneration has a large effect on the relative profitability of continuous
468 cover and rotation forestry (Tahvonen and Rämö 2016). In this study, we have assumed the cost of
469 artificial regeneration to be €1000 ha⁻¹, which is on the lower side of the typical cost range in Finland.
470 If the regeneration cost is set higher, e.g. €2000, continuous cover management is optimal regardless
471 of carbon price even with low interest rates. Low site productivity has a similar effect.

472 McKinsey & Company (2009) estimates a global abatement potential of almost 8000 MtCO₂
473 per year in the forestry sector for a marginal cost range from €2 to €28 tCO₂⁻¹. In van Kooten et al.
474 (2009), a meta-regression analysis of forest carbon storage costs is performed using 1047
475 observations from 68 studies. Depending on the regression model used, the authors obtain highly
476 varying estimates on the marginal costs of carbon storage. According to van Kooten et al. (2009),
477 storage costs are higher in the boreal region than in the tropics or than the global average. Within the
478 boreal region, their estimates are roughly equal to €4–€94 tCO₂⁻¹ for plantation activities and 34–
479 €155 tCO₂⁻¹ for adaptation of forest management. However, Niinimäki et al. (2013) show that
480 optimizing the stand management of Norway spruce yields additional discounted carbon storage up

481 to 40 tCO₂ ha⁻¹ with marginal costs in the range of €6–€36 tCO₂⁻¹.⁴ Our results, obtained using a stand-
482 level model with optimized management regime choice, point to a cost range of €5–€47 tCO₂⁻¹ with
483 as much as 70 tCO₂ ha⁻¹ of abatement potential. This suggests that if all relevant aspects of forest
484 management adaptation are optimized, increasing carbon storage can be relatively inexpensive even
485 in the boreal region.

486 In 2015 the European Union (EU) committed to reducing its domestic greenhouse gas emissions
487 by at least 40% from the 1990 level by 2030 (European Commission 2015). According to an impact
488 assessment by the Commission, fulfilling this commitment would imply a carbon price in the range
489 of €11–€53 tCO₂⁻¹ (depending on policy scenario) in the EU Emissions Trading Scheme (ETS) by
490 2030. The range of projected prices in 2050 is €85–€264 tCO₂⁻¹ (European Commission 2014, p. 80–
491 81.) Such carbon price levels would incentivize major changes in forest management, if carbon
492 storage in forests was linked to the ETS. Currently, however, New Zealand is the only country that
493 has integrated forest carbon storage in its emissions trading system (Adams and Turner 2012).
494 Whether or not similar approaches will be adopted in the EU and elsewhere, forest carbon storage is
495 likely to play an important role in any cost-effective climate change abatement strategy.

496 We have presented a way to study economically optimal carbon storage in forestry without
497 limiting the analysis to either even-aged or uneven-aged forestry. By determining the optimal
498 management regime endogenously, we can cover both regimes simultaneously and analyse the effect
499 of carbon storage on the optimal choice between them. We show that higher stand density, long
500 rotations and a possible switch to continuous cover management, with an emphasis on harvesting
501 large trees with a high sawlog ratio, are the economically efficient carbon abatement methods in stand
502 management. Optimal regime shifts between rotation forestry and continuous cover forestry in size-
503 structured stands have not previously been addressed in the carbon storage literature. The importance

⁴ Goetz et al. (2010) present even lower cost ranges for uneven-aged forestry in Spain, especially if soil carbon is taken into account.

504 of our results is further emphasized by recent arguments that forest heterogeneity (age, size and
505 species structure) may improve forest resilience under disturbances caused by climate change
506 (Gamfeldt et al. 2015). The next step, then, will be to optimize carbon storage and wood production
507 in mixed-species stands.

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Tables

Table 1. Size class -specific parameter values, per tree.

Size class	Diameter (cm)	Basal area (m ²)	Sawlog volume, $SI = 15$ (m ³)	Pulpwood volume, $SI = 15$ (m ³)
1	7.5	0.004	0.000	0.014
2	12.5	0.012	0.000	0.067
3	17.5	0.024	0.000	0.167
4	22.5	0.040	0.234	0.081
5	27.5	0.059	0.446	0.065
6	32.5	0.083	0.684	0.060
7	37.5	0.110	0.963	0.050
8	42.5	0.142	1.253	0.050
9	47.5	0.177	1.574	0.043
10	52.5	0.216	1.900	0.039
11	57.5	0.260	2.214	0.033
12	62.5	0.307	2.565	0.031

Table 2. Parameter values for the harvesting cost function.

i	C_{i0}	C_{i1}	C_{i2}	C_{i3}	C_{i4}	C_{i5}	C_{i6}	C_{i7}
th	2.100	1.150	0.412	0.758	0.180	1.000	2.272	0.535
cl	2.100	1.000	0.397	0.758	0.180	1.000	1.376	0.393

Table 3. Effect of carbon pricing on optimal stand management, given €1000 ha⁻¹ regeneration cost.

Interest rate	Carbon price	Rotation age	Timing of first harvest	Harvest interval at steady state	Diameters of trees harvested at steady state	Mean stand volume
	(€ tCO ₂ ⁻¹)	(years)	(years from stand regeneration)	(years)	(cm)	(m ³ ha ⁻¹)
2%	0	130	45	—	—	138
	10	150	45	—	—	152
	20	170	50	—	—	174
	30	∞	50	25	32.5–52.5	182
	60	∞	50	20	37.5–52.5	224
4%	0	∞	40	20	22.5–37.5	68
	10	∞	45	25	22.5–42.5	79
	20	∞	45	20	27.5–42.5	114
	30	∞	50	20	32.5–47.5	169
	60	∞	55	25	37.5–57.5	234

Table 4. Effect of carbon pricing on timber production and carbon storage, given €1000 ha⁻¹ regeneration cost.

Interest rate	Carbon price	Rotation age	Mean annual sawlog / total yield	Mean CO ₂ storage in living trees	Mean CO ₂ storage in dead tree matter	Mean CO ₂ storage in timber products	Discounted CO ₂ sequestration
	(€ tCO ₂ ⁻¹)		(m ³ ha ⁻¹ a ⁻¹)	(tCO ₂ ha ⁻¹)	(tCO ₂ ha ⁻¹)	(tCO ₂ ha ⁻¹)	(tCO ₂ ha ⁻¹)
2%	0	130	6.3 / 7.6	207	53	80	198
	10	150	6.5 / 7.6	227	53	81	213
	20	170	6.7 / 7.6	260	54	83	232
	30	∞	5.7 / 6.0	271	43	69	244
	60	∞	5.7 / 6.0	335	44	70	269
4%	0	∞	3.8 / 4.5	101	30	48	108
	10	∞	4.0 / 4.7	118	32	51	115
	20	∞	5.0 / 5.6	170	38	62	123
	30	∞	5.7 / 6.1	252	43	70	133
	60	∞	5.6 / 5.8	349	43	67	144

Table 5. Forestry revenues, given €1000 ha⁻¹ regeneration cost.

Interest rate	Carbon price	Discounted timber income	Discounted carbon subsidies	Net present value
	(€ tCO ₂ ⁻¹)	(€ ha ⁻¹)	(€ ha ⁻¹)	(€ ha ⁻¹)
2%	0	9 863	0	8 780
	10	9 791	2 128	10 865
	20	9 514	4 648	13 127
	30	9 174	7 314	15 488
	60	8 000	16 127	23 127
4%	0	2 662	0	1 662
	10	2 610	1 148	2 758
	20	2 483	2 462	3 945
	30	2 233	3 992	5 225
	60	1 726	8 666	9 392

Figure captions

Figure 1. Stand volume and number of trees, with a 2% interest rate and carbon prices €0, €10, €20 and €30 tCO₂⁻¹. Note: $w = €1000 \text{ ha}^{-1}$.

Figure 2. Stand volume and number of trees, with a 4% interest rate and carbon prices €0 and €20 tCO₂⁻¹. Note: $w = €1000 \text{ ha}^{-1}$.

Figure 3. Optimal steady-state structures expressed as (a) number of trees and (b) commercial volume in each size class, with a 4% interest rate and carbon prices €0, €10, €20 and €30 tCO₂⁻¹. Size classes begin from a diameter of 7.5 cm and increase in 5-cm intervals. Note: $w = €1000 \text{ ha}^{-1}$.

Figure 4. Total carbon storage, including carbon storage in living trees, dead tree matter and timber products, with a 2% interest rate and carbon prices €0, €10, €20 and €30 tCO₂⁻¹. Note: $w = €1000 \text{ ha}^{-1}$.

Figure 5. Marginal abatement costs. Note: $w = €1000 \text{ ha}^{-1}$.

(a) $p_c = €0 \text{ tCO}_2^{-1}$

(b) $p_c = €10 \text{ tCO}_2^{-1}$

(c) $p_c = €20 \text{ tCO}_2^{-1}$

(d) $p_c = €30 \text{ tCO}_2^{-1}$

— Stand volume, $\text{m}^3 \text{ha}^{-1}$ - - - Number of trees, ha^{-1}

(a) $p_c = €0 \text{ tCO}_2^{-1}$

(b) $p_c = €20 \text{ tCO}_2^{-1}$

— Stand volume, $\text{m}^3 \text{ha}^{-1}$ - - - Number of trees, ha^{-1}