Optimal carbon storage in generalized size-structured forestry

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Abstract

We study economically optimal carbon storage in size-structured forest stands using a generalized model that allows the choice of management regime to be made endogenously. Optimal harvests may be based only on thinnings, implying continuous cover forestry, or on both thinnings and clearcuts, implying even-aged forestry. We consider carbon stored in living trees, in dead tree matter and in timber products, and gradual carbon release from decaying dead tree matter and timber products. Forest growth is depicted using an empirically estimated transition matrix model for Norway spruce. The optimization problem is solved in its general dynamic form by applying bilevel optimization with gradient-based interior point methods and a genetic algorithm. We show that carbon pricing postpones thinnings and increases stand density by directing harvests to larger trees. Carbon pricing increases rotation age and may well imply a regime shift from clearcuts to continuous cover forestry. In continuous cover solutions, the steady state harvesting interval and the diameter distribution of the standing and harvested trees change according to carbon price. Valuing carbon storage is shown to increase the sawlog ratio of timber yields. We show that carbon storage is maintained not only in the standing trees but also in in timber products, and to a lesser extent in dead tree matter. Additionally, we present estimates of the marginal costs of carbon storage on stand level.

Keywords: carbon storage, carbon subsidy, continuous cover forestry, optimal rotation, uneven-aged forestry

JEL classifications: Q23, Q54

1. Introduction

The importance of forests for the mitigation of climate change is well established (IPCC 2000, 2014). Forest ecosystems are a crucial part of the global carbon cycle, and hold more than double the amount of carbon in the atmosphere (FAO 2006). Cost-efficient methods for maintaining and improving carbon storage in forests are therefore essential. While carbon storage potential, costs and scheme designs have been studied at the national level (e.g. Lubowski et al. 2006, Mason and Plantinga 2013), important stand level questions still remain unexplored. Our study analyzes optimal carbon storage in size-structured stands using a novel forest economic model that encompasses both forest management based on clearcuts and management that maintains forest cover continuously. With such a generalized model, we can cover both management regimes simultaneously, and analyze the effect of carbon storage on the optimal choice between these alternatives.

Especially in the boreal region, forest practices have relied heavily on the rotation regime, where forest stands are artificially regenerated and finally clearcut, resulting in even-aged stands (Gauthier et al. 2009). In resource economics this management system is typically analyzed using the Faustmann optimal rotation model (Samuelson 1976). The model, sometimes extended to include partial cuttings (i.e. thinnings) before the clearcut, is well suited for planted even-aged forests. However, such forests account for only 13% of managed forest area globally (Payn et al. 2015, FAO 2010). Further, diversification of forest management practices, even in such areas that are currently dominated by homogenous even-aged forests, may be necessary to maintain forest resilience in the face of disturbances related to climate change (Gauthier et al. 2015).

Interest in forest management alternatives such as continuous cover forestry has been increasing lately (Puettmann et al. 2009). Continuous cover forestry (or uneven-aged forest management) implies partial cuttings that typically target the largest tree-classes. Regeneration takes place naturally, resulting in a heterogeneous size distribution. Continuous cover forestry entails some ecological advantages: compared to even-aged forests, uneven-aged forests are likely to be more favorable to many forest-dwelling species (Calladine et al. 2015) and more resilient against climate change and other threats (Thompson et al. 2009, Gauthier et al. 2015, Björkman et al. 2015). The main economic advantage of continuous cover forestry is that it lacks the expensive initial investment in artificial regeneration.

Up to very recently, the economics of even-aged and uneven-aged forestry have been analyzed separately, using completely different models. While the large body of literature on even-aged forestry extends from the classic study by Faustmann (Faustmann 1849, Samuelson 1976), the first attempts to optimize uneven-aged management include de Liocourt (1898) and Adams and Ek (1974). As discussed in Getz and Haight (1989, p. 287–295), Tahvonen (2011) and Rämö and Tahvonen (2014), many studies have attempted to bypass the dynamic complexities involved in optimizing uneven-aged forestry. Seminal contributions by Haight (1985) and Haight and Getz (1987) present the uneven-aged problem as an infinite time horizon problem without *ad hoc* restrictions.

Recently it has been shown that when the optimal choice between continuous cover *vs*. clearcut forest management is determined endogenously, both management regimes can be analyzed using the same model (Tahvonen and Rämö 2016). This generalized approach for size-structured stands allows for the optimization of stand management – thinnings and the (potentially infinite) rotation age – over an infinite time horizon given any initial state. The results suggest that high site productivity, low interest rate and low regeneration cost favor the clearcut regime instead of continuous cover regime, and *vice versa* (Tahvonen and Rämö 2016). The study at hand extends this model by including subsidized forest carbon storage.

The clear majority of research on forest carbon storage has analyzed exclusively even-aged management. Given that adaptation to climate change may call for more heterogeneous forests, this is a severe limitation. The seminal paper by van Kooten et al. (1995) examines the effect of carbon taxes and subsidies on optimal rotation age and supply of carbon services using the Faustmann optimal rotation model. The authors find that carbon pricing generally increases rotation ages only moderately but might in some cases yield the result that it is optimal to forgo harvesting completely. Hoel et al. (2014) extend this model by including forests' multiple carbon pools, harvest residues and use of timber for bioenergy. Both van Kooten et al. (1995) and Hoel et al. (2014) exclude partial cuttings (i.e. thinnings), which is a strong simplification in e.g. Nordic context.

Thinnings are included in the problem of optimal carbon storage in even-aged forestry in e.g. Huang and Kronrad (2006), Pohjola and Valsta (2007) and Daigneault et al. (2010). Further research on economically optimal carbon storage in even-aged stands include Niinimäki et al. (2013) for Norway spruce and Pihlainen et al. (2014) for Scots pine, both computed using a detailed process-based model. These studies, especially Niinimäki et al. (2013) on Norway spruce, highlight the importance of adapting thinning strategies (in addition to the rotation period) for economically optimal carbon storage.

To date, economic research on carbon storage in uneven-aged forest management has been very limited. While Gutrich and Howarth (2007) focus on the optimization of rotation age in clearcut management without thinnings, they also present comparisons to (un-optimized) continuous cover management which is shown to be a viable option for carbon storage. Goetz et al. (2010) present a model for determining the optimal selective harvesting and planting regime for Scots pine in Spain when considering timber production and carbon storage, but do not consider the option of clearcutting.

The study at hand numerically applies a size-structured growth model with an empirically estimated Scandinavian growth model for Norway spruce. As far as we know, this is the first study to analyze optimal carbon storage in size-structured stands using a model-setup that allows the choice between clearcuts and continuous cover forestry to be made endogenously. Additionally, the present study features a detailed economic setup with empirically estimated variable harvesting cost functions, as well as fixed harvesting costs that necessitate the optimization of thinning intervals. This is essential for accurately determining the relative economic performance of the clearcut regime and continuous cover forestry. We extend the van Kooten et al. (1995) carbon storage formulation to explicitly include the carbon dynamics in the whole tree biomass, in dead tree matter and in timber products with distinct decay rates for sawlog and pulpwood products.

We show that when carbon storage has economic value, thinnings are somewhat postponed and target larger trees than without carbon pricing, implying higher stand volume. Subsidized carbon storage increases rotation age and may imply a management regime shift from clearcuts to continuous cover forestry. Moderate carbon pricing tends to increase timber supply from the stand, especially sawlog. We show that in optimal solutions, carbon storage is maintained not only in the stand but also in timber products.

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

2. The growth model and the optimization problem

We assume that the stand is artificially regenerated after a clearcut, and the time interval between the regeneration activities and the ingrowth of trees into the smallest size class equals some number of periods denoted by $\hat{t}$. Thus, $\hat{t}$ periods after the artificial regeneration (i.e. after the planting delay), we have an initial stand composed of a given number of trees in size class 1. The stand is clearcut if the rotation length $T \in [\hat{t}, \infty)$ is finite. We denote the number of trees in size class s at the beginning of period t by x_{st}, $s = 1, 2, ..., n$, $t = \hat{t}, \hat{t}+1, ..., T$. Accordingly, the stand state at period t can be given as $\mathbf{x}_t = [x_{1t}, x_{2t}, \dots, x_{nt}]$. Let us denote the fraction of trees moving to size class $s+1$ at period t by $\beta_s(\mathbf{x}_t)$, $s=1,2,...,n$, and the natural mortality in size class s at period t by $\mu_s(\mathbf{x}_t)$, $s=1,2,...,n$. Thus the fraction of trees staying in the same size class equals $1-\beta_s(\mathbf{x}_t)-\mu_s(\mathbf{x}_t)$, $s=1,2,...,n$. Ingrowth, i.e. new small trees, at the beginning of period t is denoted by $\phi(\mathbf{x}_t)$. Additionally, we denote the number of trees harvested from size class s at the end of period t by h_{st}, $s=1,2,...,n,\ t=\hat{t},\hat{t}+1,..,T$. Hence, following Getz and Haight (1989, p. 237–239), the stand development can be described by the difference equations

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

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

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

where $t=\hat{t},\hat{t}+1,...,T$.

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

$$R(\mathbf{h}_t)=\sum_{s=1}^{n}h_{st}\left(v_{\sigma,s}p_\sigma+v_{\varpi,s}p_\varpi\right),\ t=\hat{t},\hat{t}+1,...T\ , \tag{4}$$

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 are the respective (roadside) prices (€). Harvesting costs are given separately for thinning and clearcuts by $C_i(\mathbf{h}_t)$, $i=th,cl$. The harvesting cost includes a fixed cost denoted by C_f. Hence, it may not be optimal to harvest the stand in every period. This is taken into account by the binary variables $\delta_t:\mathbb{Z}\in[0,1],\ t=\hat{t},\ \hat{t}+1,...,T$ and by the Boolean operator $h_t=\delta_t h_t$. When the choice is

$\delta_t = 1$, the levels of $h_{st} \geq 0,\ s = 1,2,...,n$ can be freely optimized. When $\delta_t = 0$, the only admissible choice is $h_{st} = 0,\ s = 1,2,...,n.$

In order to internalize the value of carbon storage services produced by forests, the society may pay the forest owner a Pigouvian subsidy for the carbon that is sequestered by the stand (c.f. van Kooten et al. 1995). Let $p_c \geq 0$ (€ tCO_2^{-1}) denote the economic value of one CO_2 unit. In the most general carbon subsidy setting, the society pays subsidies according to the amount of CO_2 that is absorbed as the stand grows, and charges for the amount of CO_2 that is released as a consequence of harvesting and decay of dead tree matter.

Let $\omega_t = \sum_{s=1}^{n} x_{s,t}\left(v_{\sigma,s} + v_{\varpi,s}\right)$ denote merchantable timber volume (i.e. stem volume) in the stand in the beginning of period *t*. Density factor ρ converts stem volume to stem dry mass. In addition to the stem, trees are comprised of non-merchantable matter, i.e. foliage, branches, bark, stump and roots. Expansion factor η converts stem dry mass into whole tree dry mass. Hence the total tree biomass in the stand can be given as $B_t = \rho\eta\omega_t$. The amount of CO_2 in one dry mass unit equals θ.

We denote the dry mass of sawlog and pulpwood harvested at the end of period *t* by $y_{\sigma,t} = \rho\sum_{s=1}^{n} h_{st} v_{\sigma,s}$ and $y_{\varpi,t} = \rho\sum_{s=1}^{n} h_{st} v_{\varpi,s}$, respectively. Logging will not instantly release the carbon content of timber into the atmosphere because it is only gradually released from timber products as they decay (Pihlainen et al. 2014, cf. Goetz et al. 2010). The urgency of mitigating climate change implies that the society is likely to have a positive time preference for net emissions. Denoting the annual decay rate of a timber assortment *j* ($j = \sigma, \varpi$) by g_j, it can be shown that the present value of future emissions (per unit of timber assortment *j*) due to product decay is

$$\alpha_j(r) = \frac{g_j}{g_j + r}. \tag{5}$$

Dead tree matter is created both through natural mortality and from the harvest residue (i.e. non-merchantable parts) of the harvested trees left in the forest. The dry mass of dead tree matter formed through natural mortality in period *t* equals $d_{m,t} = \rho\eta\sum_{s=1}^{n}\mu(\mathbf{x}_t)_{s,t}\, x_{s,t}\left(v_{\sigma,s} + v_{\varpi,s}\right)$. Further, the dry mass of harvest residue created in the end of period *t* can be given as $d_{h,t} = (\eta - 1)\left(y_{\sigma,t} + y_{\varpi,t}\right)$. Denoting the decay rate of dead tree matter by g_d, the (per unit) present value of future emissions due to this decay equals

$$\alpha_d(r) = \frac{g_d}{g_d + r}. \tag{6}$$

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

$$Q_t = p_c\theta\left\{B_{t+1}(\mathbf{x}_{t+1}) - B_t(\mathbf{x}_t) + \left[1-\alpha_\sigma(r)\right]y_{\sigma,t}(\mathbf{h}_t) + \left[1-\alpha_\varpi(r)\right]y_{\varpi,t}(\mathbf{h}_t) + \left[1-\alpha_d(r)\right]\left(d_{m,t}(\mathbf{x}_t) + d_{h,t}(\mathbf{h}_t)\right)\right\} \tag{7}$$

for $t = \hat{t}, \hat{t}+1, ..., T$. During the planting delay ($t = 0,1,...,\hat{t}-1$), we assume linear stand volume growth implying constant carbon sequestration. The carbon storage formulation presented above is considerably more detailed than the one applied in van Kooten et al. (1995).

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

$$J(\mathbf{x}_0, T) = \max_{\{h_{st}, \delta_t, T\in[0,\infty)\}} \frac{-w + \sum_{t=0}^{T} Q(\mathbf{x}_t, \mathbf{h}_t)b^{\Delta(t+1)} + \sum_{t=\hat{t}}^{T}\left[R(\mathbf{h}_t) - C_i(\mathbf{h}_t) - \delta_t C_f\right]b^{\Delta(t+1)}}{1 - b^{\Delta(T+1)}} \tag{8}$$

s.t. (1) – (3) and

$$h_{st} \geq 0, \quad x_{st} \geq 0, \quad s = 1,2,...,n, \quad t = \hat{t}, \hat{t}+1, ..., T, \tag{9}$$

$$\mathbf{h}_T = \mathbf{x}_T, \tag{10}$$

$x_{s,0}$ given. (11)

The optimal forest management regime is determined by the choice of *T*. If – given optimized thinnings – the objective function is maximized by a finite rotation age, clearcut management is optimal. If no finite optimal rotation age exists, it is optimal to apply continuous cover management.

3. Ecological and economic parameter values

We apply an empirically estimated growth model by Bollandsås et al. (2008) for Norway spruce at the latitude of 61.9 ºN. The model includes 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) meters. We use 12 size classes with diameters (midpoints) ranging from 7.5 cm to 62.5 cm with 5.0 cm intervals. Table 1 presents the size class specific parameter values (Rämö and Tahvonen 2014). The initial stand structure is given as **x** = [2250, 0, 0, …], i.e. after artificial regeneration and the planting delay, 2250 trees will emerge in the smallest size class. The length of a period (Δ) is five years and the planting delay is 20 years.

The fraction of trees moving to the next size class during period t is denoted by

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

where L_{st} is the total basal area of size classes $s+1,...,n$ in the beginning of period *t*.

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

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

$$\mu_{st} = \left(1 + e^{-\left(-2.492 - 0.020 M_s + 3.2 \cdot 10^{-5} M_s^2 + 0.031 A_t\right)}\right)^{-1},$$

where M_s is the diameter (midpoint) of size class s and A_t the total stand basal area (m^2 ha^{-1}) in the beginning of period t. The estimated number of trees entering the smallest size class during the 5-year period t is given as

$$\phi_t = \frac{54.563\left(A_t + a\right)^{-0.157} \cdot SI^{0.368}}{1 + e^{\left(0.391 + 0.018 A_t - 0.066 \cdot SI\right)}}.$$

Note that ϕ is strictly convex in $\mathbf{x}$ implying nonconvexities in the optimization problem. In Bollandsås et al. (2008) $a = 0$ and $\phi \to \infty$ as $\mathbf{x} \to 0$. This feature is unwarranted, and based on Wikberg (2004) and Pukkala et al. (2009) we set $a = 0.741$, which implies $\phi(0) = 100$. This parameter has negligible effects and decreases the ingrowth by less than one tree per year when basal area is above 2 m^2.

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

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

C_{i0} is the per minute cutting cost (€), and its coefficient $C_{i1}(\bullet)$ is the time (in minutes) spent in cutting one tree (and moving the machinery to the next). C_{i5} and its coefficient $[\bullet]$ are the cost and time spent in hauling, respectively, and $v_s = v_{\sigma,s} + v_{\varpi,s}$ is the volume of a tree in size class s. The parameter values for C_{ik}, $i = th, cl$, $k = 0,...,7$ ($th = thinning$, $cl = clearcut$) are given in Table 2.

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

The parameter $C_{th1} = 1.150$ in the cutting cost element for thinning takes into account that cutting one tree and moving to the next one is more costly in (continuous cover) thinning compared with clearcuts (Surakka and Siren 2007). Hauling in thinning is additionally more time-consuming compared with clearcuts.

The stemwood density factor (ρ) for Norway spruce is 0.3774 tonnes of dry matter per cubic metre of fresh volume (Lehtonen et al. 2004). Based on Lehtonen et al. (2004), expansion factor to convert stem dry mass into whole tree dry mass (η) equals 2.1566. The CO_2 content of a wood dry mass unit (θ) is obtained by multiplying the share of carbon in biomass dry weight (0.5) with the coefficient that converts tonnes of carbon to tonnes of CO_2 (44/12) (Niinimäki et al. 2013). Thus we set $\theta = 1.83333$ tCO_2 t^{-1}. For the decay rate of dead tree matter we use g_d = 0.18196 based on Hyvönen and Ågren (2001). To obtain the decay rates for sawlog and pulpwood products we use data presented in Liski et al. (2001) on the division of sawlog and pulpwood removals for production lines, on production losses, and on the division into timber product types with different life-spans. The obtained parameter values are g_σ = 0.06611 and g_ϖ = 0.47070.

4. Computational methods

Because the variables $\delta_t : \mathbb{Z} \in [0,1], t = \hat{t}, \hat{t}+1,...,T$ are integers but $h_t = \delta_t h_t$, $s = 1,2,...,n$, $t = \hat{t}, \hat{t}+1,...,T$ are continuous, the task is to solve a mixed-integer nonlinear programming problem. To do this, we apply bilevel optimization (Colson et al. 2007) where optimizing the binary variables is the upper-level problem and optimizing the continuous variables the lower-level problem. A similar approach has been applied to a forest management problem without carbon storage in Tahvonen and Rämö (2016). The lower-level problem is computed using version 9.0 of Knitro optimization software that applies advanced gradient-based interior point algorithms (Byrd et al. 2006). The maximized objective value of the lower level problem forms the objective value given any vector of harvest timing binaries. The harvest timing vector is optimized using a genetic algorithm (Deb and Sinha 2010). The optimal harvest schedules are solved for a series of rotation lengths. If the objective function obtains a maximum with some $T \in [60,180)$ years, the optimal rotation is finite. If the value of the objective function keeps on increasing as the rotation period is lengthened, the optimal rotation is infinite. In this case, the optimal continuous cover solution is obtained by lengthening the horizon to obtain a close approximation of the infinite horizon solution. In order to handle potential non-convexities, we apply multiple randomly chosen initial points for both algorithms.

5. Results

The effects of carbon pricing on optimal stand management

Given an annual interest rate of 2%, optimal rotation age increases with carbon price (Table 3, Figure 1). The rotation length without carbon pricing equals 130 years. The relatively long rotation age follows from optimally utilizing natural regeneration during the rotation. When carbon price equals €10 (€20) tCO_2^{-1}, the optimal rotation age increases is 150 (170) years. Given a carbon price of €30 tCO_2^{-1} or higher, the optimal rotation age is infinite, implying that continuous cover forestry is superior to clearcutting (Table 3). Given 4% interest rate, the optimal rotation is infinite even with zero carbon price. This is because high interest rate makes it optimal to postpone or avoid the investment in artificial regeneration, as natural regeneration maintains a sufficient growth without costs. Additionally, the time delay between stand regeneration and the first revenues from thinnings becomes costly when discounting is heavier.

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	n/a	n/a	138
	10	150	45	n/a	n/a	152
	20	170	50	n/a	n/a	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

Given 2% interest rate and zero carbon price, the first thinning takes place 45 years after stand regeneration. Carbon pricing postpones the first thinning by five years and increases mean stand volume along the rotation – or, in the case of continuous cover solutions, stand volume at steady state (Table 3). The timing and intensity of subsequent thinnings can be seen in Figure 1, where stand volume and number of trees drop after each harvest. Given 4% interest rate and no carbon pricing, thinning begins already at the stand age of 40 years (Table 3). A carbon price of €10 (€60) tCO_2^{-1} postpones the first thinning by 5 (15) years. Regardless of management regime (clearcuts or continuous cover forestry), optimal thinning is invariably done from above, always fully cutting down the largest harvested size class. The relative value growth is very high in small trees, implying that it is optimal to postpone harvesting until they have grown to a size that yields sawlog.

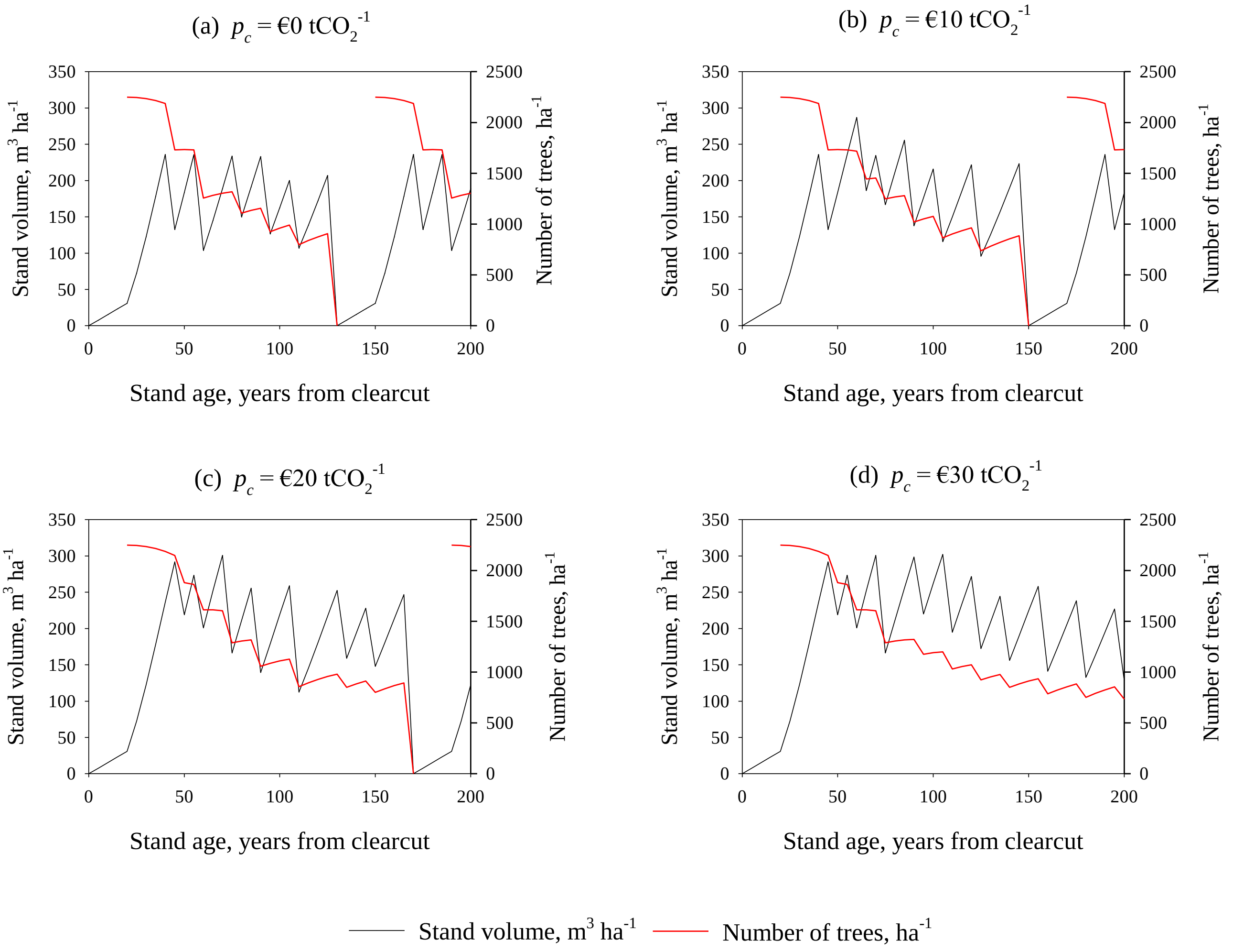

Figure 1. Stand volume and number of trees, with 2 % interest rate and carbon prices €0, €10, €20 and €30 tCO_2^{-1}. Note: w = €1000 ha^{-1}.

While higher interest makes it optimal to maintain less capital in the stand, carbon pricing works in the opposite direction: the higher the carbon price, the larger are the harvested trees at continuous cover steady states (Table 3, Figure 2). Additionally, trees are harvested from as many size classes as is the number of five-year-periods between the steady state harvests. Given 2% interest rate and a carbon price of €30 tCO_2^{-1}, trees are harvested from five size classes (diameter midpoints 32.5, 37.5, 42.5, 47.5, and 52.5 cm) with a 25 year interval. When carbon price increases to €60 tCO_2^{-1}, it is optimal to forgo harvesting the 32.5 cm diameter class and to only cut trees with diameters of 37.5 – 52.5 cm. This is achieved by switching to a 20-year harvesting interval (Table

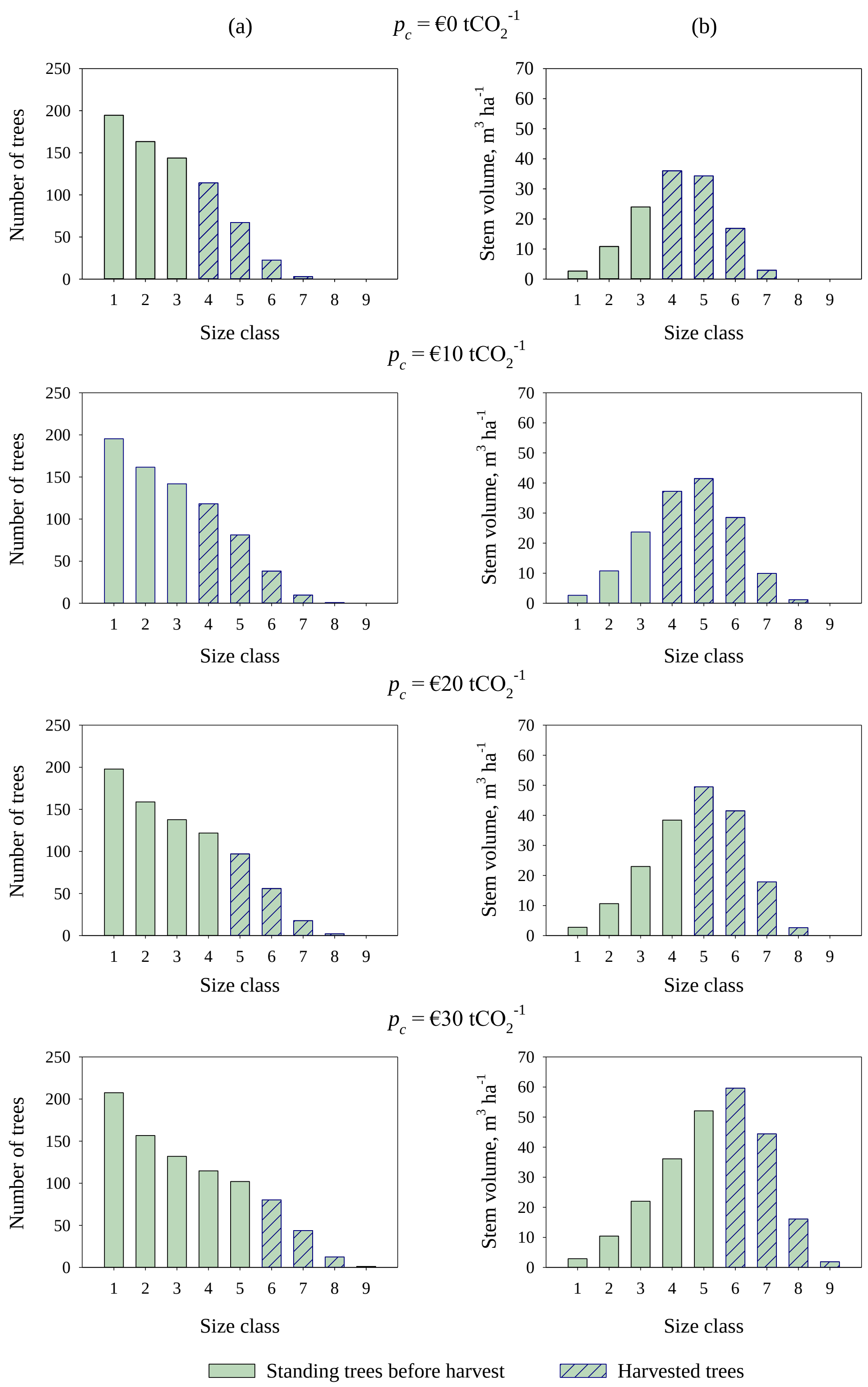

Figure 2. Optimal steady-state structures expressed as (a) number of trees and (b) stem volume in each size class, with 4 % interest rate and carbon prices €0, €10, €20 and €30 tCO_2^{-1}. Size classes begin from a diameter of 7.5 cm and increase in 5 cm intervals. Note: w = €1000 ha^{-1}.

3). Thus harvest timing adjusts to the carbon price in order to maintain optimal average stand density and economic return (including carbon subsidies) along the harvest interval.

Given 4% interest rate and zero carbon price, steady state harvest takes place every 20 years, and targets trees with diameters of 22.5 – 37.5 cm (Table 3, Figure 2). With a €10 tCO_2^{-1} carbon price, the steady state harvesting interval equals 25 years, allowing some of the trees to enter the 42.5 cm size class before they are harvested. Increasing the carbon price further shifts steady state harvests to larger size classes, implying higher mean stand volume (Table 3). The diameter distributions in continuous cover steady states (Figure 2, column a) resemble a reverse-J form: the number of trees decreases with tree size class (cf. de Liocourt 1898, Usher 1966). However, large trees comprise a considerable fraction of the total stem volume because of their high volume per tree (Figure 2, column b).

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

The effects of carbon pricing on timber production and carbon storage

Given 2% interest rate and zero carbon price, mean annual sawlog yield over the rotation equals 6.3 m^3 ha^{-1}, while the mean annual total yield (sum of sawlog and pulpwood) equals 7.6 m^3 ha^{-1} (Table 4). Increasing the carbon price to €10 (€20) tCO_2^{-1} increases mean sawlog yield to 6.5 (6.7) m^3 ha^{-1} while total yield remains unchanged, i.e. the sawlog-pulp ratio increases. This has a positive effect on carbon storage because the typical decay of sawlog products is notably slower than that of pulpwood. Increasing the carbon price to €30 tCO_2^{-1} implies a regime shift from clearcuts to continuous cover forestry, and decreases mean sawlog and total yield but increases the sawlog ratio. This is because in the clearcutting solutions, large yields are produced by the intensive thinning of the large initial cohort and in the clearcut. These peaks are absent from the continuous cover steady state. Increasing the carbon price further, to €60 tCO_2^{-1}, has only a negligible effect on mean sawlog and total yields.

Given 4% interest rate and no carbon pricing, mean sawlog and total yields are low, 3.8 and 4.5 m^3 ha^{-1} a^{-1}, respectively (Table 4). This is due to the low optimal level of growing capital. With carbon pricing, trees are allowed to grow bigger before they are harvested (Table 3), which increases yields up to a point. E.g. given carbon price of €30 tCO_2^{-1}, mean sawlog yield equals 5.7 m^3 ha^{-1} and mean total yield is 6.7 m^3 ha^{-1}. However, with €60 tCO_2^{-1} carbon price, mean sawlog and total yields equal 5.6 and 5.8 m^3 ha^{-1}, respectively (Table 4). This implies that when the carbon price is sufficiently high, yields start to decrease with carbon price because only very large trees are harvested.

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 negative CO_2 emissions
	(€ 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

In economically optimal solutions, natural mortality remains low but dead tree matter is generated from harvest residues. Each harvest decreases carbon storage in living trees but causes a temporary increase in carbon storage in dead tree matter and in timber products (Figure 3). The latter two, however, quickly decrease as a consequence of decay. This is especially true for clearcuts (Figure 3a–c), which yield large amounts of fast decaying pulpwood. Because of

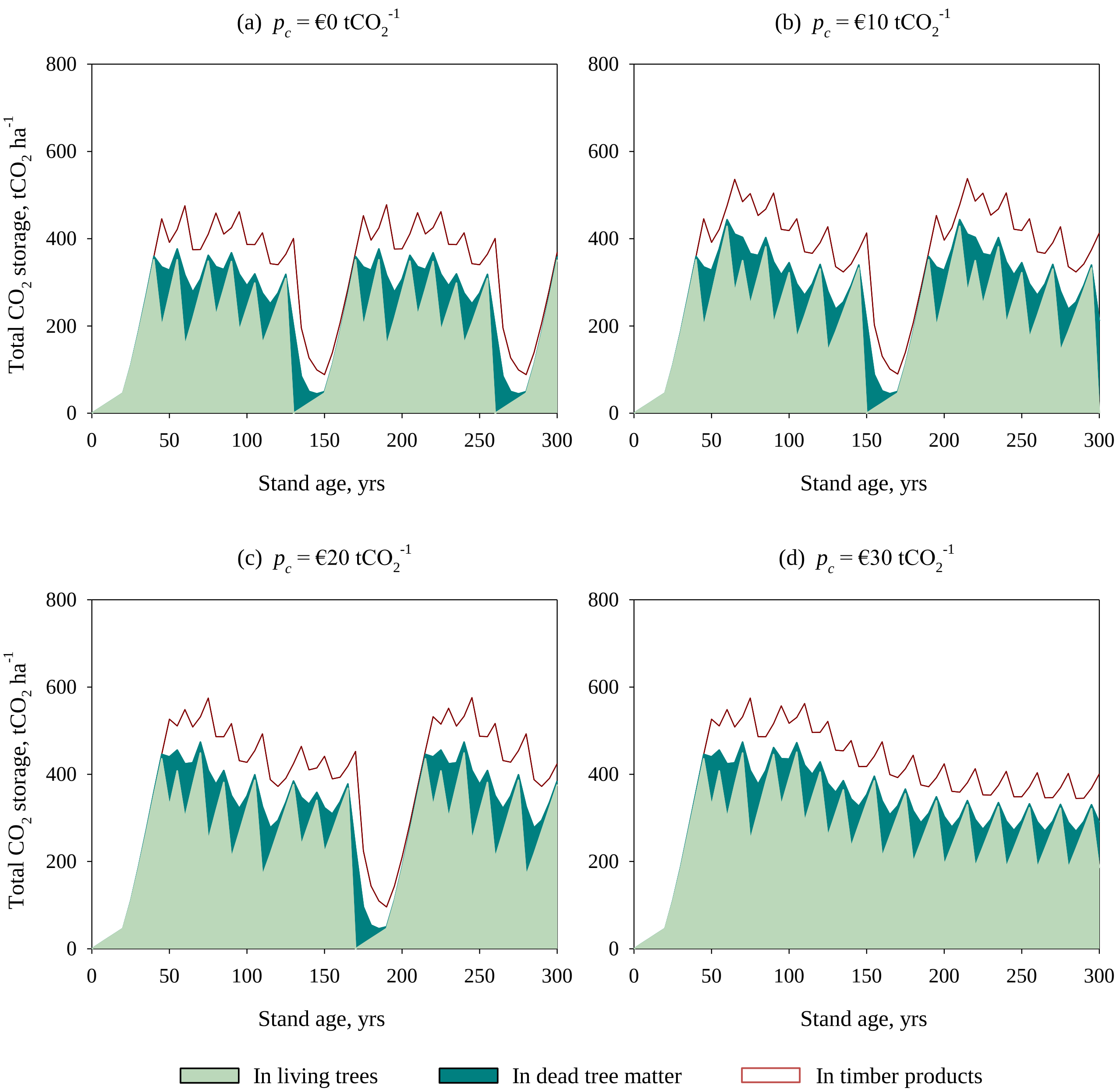

Figure 3. Total carbon storage, including carbon storage in living trees, dead tree matter and timber products, with 2% interest rate and carbon prices €0, €10, €20 and €30 tCO_2^{-1}. Note: w = €1000 ha^{-1}.

exponential decay, the initial carbon stocks in dead tree matter and in timber products reach a steady state where total carbon storage in the beginning of the rotation equals total carbon storage in the end of the rotation (e.g. the third rotation in Figure 3a). In continuous cover solutions (Figure 3d) carbon stocks in living trees, in dead tree matter and in timber products go through a transition phase before reaching a steady state.

Mean carbon storage in living trees increases with carbon price (Table 4). E.g. given 2 % interest rate and no carbon pricing, the average amount of carbon that is stored in living trees over a rotation corresponds to 207 tCO_2 ha^{-1}; increasing the carbon price to €60 tCO_2^{-1} increases mean storage to 335 tCO_2 ha^{-1}. Additionally, mean carbon storage in dead tree matter and in timber products generally increase with carbon price. An exception is the regime shift from clearcuts to continuous cover forestry (2% interest rate, carbon price from €20 to €30 tCO_2^{-1}). As mentioned, clearcut management produces high total yields and thus large amounts of harvest residue. Moreover, the calculation of mean carbon storage in dead tree matter and in timber products takes into account the accumulation of these stocks from one rotation to the next.

In the solutions where continuous cover management is optimal, the steady state may be reached as late as approximately 300 years after stand regeneration. This implies that in terms of economic welfare, the carbon storage taking place during the long transition phase towards the steady state is likely to be more important than mean carbon storage. Discounted negative CO_2 emissions (tCO_2 ha^{-1}) is the sum of all periodic net carbon fluxes within the infinite planning horizon, each discounted to the present (stand regeneration) moment. For example, given 2 % interest rate and a carbon price of €20 tCO_2^{-1}, the net carbon sequestration over the infinite horizon is equivalent to 232 tons of CO_2 emissions abated immediately. Discounted negative CO_2 emissions increase monotonously with carbon price (Table 4).

Forestry revenues and the cost of carbon storage

Discounted timber income is the lower, the higher the carbon price (Table 5). This is despite of the fact that mean timber yields do not monotonically decrease with carbon price (Table 4). The decrease in discounted timber income is partly explained by differences in the timing of harvests: when carbon storage is valued, harvests are carried out later. Additionally, deviating from the optimal timber-only solution implies higher harvesting costs per timber unit. However, the decrease in timber income is more than compensated by the carbon subsidies implying that carbon subsidization improves net present values (i.e. bare land value). Given 2% (4%) interest rate, a carbon price of €20 tCO_2^{-1} increases bare land value by 50% (137%) (Table 5).

The economic cost of additional carbon storage, i.e. the cost of CO_2 emissions abatement in forestry, is measured as lost timber income. To obtain average abatement cost for each carbon price, we divide the change (from baseline case, i.e. solution without carbon pricing) in timber income by the increase in discounted negative CO_2 emissions (relative to baseline). The average abatement

Table 5. Forestry revenues and the cost of abatement, given €1000 ha^{-1} regeneration cost.

Interest rate	Carbon price (€ tCO_2^{-1})	Discounted timber income (€ ha^{-1})	Discounted carbon subsidies (€ ha^{-1})	Net present value (€ ha^{-1})	Average abatement cost (€ tCO_2^{-1})	Marginal abatement cost (€ tCO_2^{-1})
2 %	0	9 860	0	8 778	0	-
	10	9 790	2 128	10 864	5	5
	20	9 513	4 648	13 126	10	14
	30	9 174	7 314	15 488	15	30
	60	8 000	16 127	23 127	26	47
4 %	0	2 662	0	1 662	0	-
	10	2 610	1 148	2 758	8	8
	20	2 483	2 462	3 945	12	15
	30	2 233	3 992	5 225	17	25
	60	1 726	8 666	9 392	26	45

cost ranges from €5 to €26 tCO_2^{-1} for the carbon prices €10 – €60 tCO_2^{-1} (Table 5). Marginal abatement cost for each carbon price level is calculated by dividing the incremental decrease in timber income by the incremental increase in discounted negative CO_2 emissions. The marginal abatement costs increase with the amount of abated emissions, and are somewhat higher than the average abatement costs (Table 5).

6. Discussion and conclusions

It is widely established in the literature that valuing carbon storage increases optimal rotation age in even-aged forestry (e.g. van Kooten et al. 1995, Stainback and Alavalapati 2002, Gutrich and Howarth 2007, Pohjola and Valsta 2007, Pihlainen et al. 2014). While our findings support this result, our model differs from previously published models in many important aspects and is able to shed light on previously unaddressed questions. Unlike many studies, we include optimized thinnings, and also optimize their timing. Further, we determine the optimal management regime – clearcuts or continuous cover forestry – endogenously. As far as we know, such an optimization approach has not been combined with carbon storage using a size-structured description of forest resources.

Including thinnings is essential for our approach because it implies that timber sales revenues may be obtained from a forest that is never clearcut. This is not the case in studies applying the classic Faustmann rotation model., e.g. van Kooten et al. (1995) and Hoel et al. (2014). According to the numerical results of van Kooten et al. (1995), carbon subsidies increase rotation age, but with plausible carbon prices the effect is usually moderate. However, in some cases it may be optimal never to harvest (i.e. to clearcut) the stand. Hoel et al. (2014) show analytically that in general, rotation age increases with the social cost of carbon and may become infinitely long. According to our results, carbon pricing may render the optimal rotation infinitely long, implying continuous cover forestry instead of total abandoning of harvesting as in van Kooten et al. (1995) and Hoel et al. (2014).

The question of optimal carbon storage in artificially regenerated even-aged stands is extended to include optimized thinnings in e.g. Pohjola and Valsta (2007), Daigneault et al. (2010) and Niinimäki et al. (2013). According to these studies, carbon pricing tends to postpone thinnings, increase stand volume along the rotation and lengthen the optimal rotation period. Our results support these findings. However, our generalized model yields optimal solutions that go beyond the scope of earlier studies that are limited to planted forests without natural regeneration. Given low interest rate (2%), optimal rotations are long, ranging from 130 to 170 years for carbon prices €0–€20 tCO_2^{-1}. With a €30 tCO_2^{-1} carbon price, clearcutting is suboptimal, i.e. the optimal management regime switches from clearcuts to continuous cover forestry. Given a higher interest rate (4%), continuous cover forestry dominates clearcutting regardless of carbon price, and management adapts to carbon pricing by changing the timing and targeting of thinnings. If natural regeneration is excluded from our model by setting $\phi(\mathbf{x}_t)=0$ in Eq. 1 (implying that any undergrowth in the stand is cleared away, and the clearing is costless) we obtain rotation ages in line with Niinimäki et al. (2013). In this case, given 2% interest rate, optimal rotation lengths range from 100 to 155 years for carbon prices €0–€60 tCO_2^{-1}. Given 4% interest rate, rotation periods for carbon prices €0–€30 tCO_2^{-1} span from 100 to 130 years, while a carbon price of €60 tCO_2^{-1} yields an optimal rotation as long as 215 years.

With the exception of Goetz et al. (2010), studies on uneven-aged management with carbon storage apply static optimization that does not allow optimizing the transition of the stand from any initial state not close to the steady state (e.g. Pukkala et al. 2011, Buongiorno et al. 2012). Further, as far as we know, the study at hand presents the first results on optimal harvest timing in uneven-aged forestry with carbon storage. Our results suggest that when starting from bare land, the large initial cohorts are intensively utilized in a series of thinnings before approaching the steady state, and that these thinnings are postponed and moderated by carbon pricing. Reaching the steady state may take as much as 300 years from stand regeneration, which emphases the importance of the transition phase for the present value of net revenues from both timber production and carbon storage. We also show that the steady state harvesting interval, as well as the diameter distribution of the standing and harvested trees, change according to carbon price. The average size of the harvested trees increases with carbon price, and 4 (or 5) diameter classes are fully harvested each 20 (25) years at the steady state.

The carbon storage formulation presented in van Kooten et al. (1995) takes into account that while carbon is stored in living trees, it may also be stored in timber products to some extent. We add detail to this formulation by explicitly including carbon storage in timber products and in dead tree matter. Our results suggest that a small storage of carbon is maintained in dead tree matter, formed mainly from the non-merchantable parts of harvested trees. Carbon pricing tends to increase this amount.

To account for carbon storage in timber products, we use distinct decay rates for sawlog and pulpwood (cf. Pihlainen et al. 2014). This is important because our size-structured model enables us to direct thinnings to trees of specific size, making use of the fact that large trees yield relatively more sawlog than small trees. Sawlog is superior to pulpwood in its ability to store carbon for extended periods. In clearcuts such targeted harvesting is by definition impossible. This inevitably results in the harvesting of quickly decaying pulpwood, which becomes costly with a high carbon price. This implies that the impact of carbon storage on the relative profitability of clearcutting *vs*. continuous cover forestry cannot be fully captured by a model that omits the size structure of the stand. According to our results, carbon pricing indeed increases the sawlog-pulp ratio of the mean annual yield and may induce a regime shift from clearcuts to continuous cover forestry.

McKinsey & Company (2009) estimates a global abatement potential of almost 8000 $MtCO_2$ per year in the forestry sector for a marginal cost range from €2 to €28 tCO_2^{-1}. In van Kooten et al.

(2009), a meta-regression analysis of forest carbon storage costs is performed using 1047 observations from 68 studies. Depending on the regression model used, the authors obtain highly varying estimates on the marginal costs of carbon storage. According to van Kooten et al. (2009), storage costs are higher in the boreal region than in the tropics or than the global average. Within the boreal region, their estimates are roughly equal to €4–€94 tCO_2^{-1} for plantation activities and 34–€155 tCO_2^{-1} for adaptation of forest management. However, Niinimäki et al. (2013) show that optimizing the management of Norway spruce yields discounted carbon storage (i.e. discounted negative CO_2 emissions) up to 200 tCO_2 ha^{-1} with marginal costs in the range of €6–€36 tCO_2^{-1}. Our results, obtained using a more general forestry model, point to a very similar cost range. This suggests that if forest management adaptation is optimized, increasing carbon storage can be relatively inexpensive even in the boreal region.

In 2015 the European Union committed to reducing its domestic greenhouse gas emissions by at least 40% from the 1990 level by year 2030 (European Commission 2015). According to an impact assessment by the Commission, fulfilling this commitment is expected to imply a carbon price in the range of €11–€53 tCO_2^{-1} (depending on policy scenario) in the EU Emissions Trading Scheme in 2030. The range of expected prices in 2050 is €85–€264 tCO_2^{-1}. (European Commission 2014, p. 80–81.) Thus carbon prices are likely to reach levels that would incentivize major changes in forest management, were carbon storage in forests linked to the ETS. Currently however, New Zealand is the only country that has integrated forest carbon storage in its emissions trading system (Adams and Turner 2012). Whether or not similar approaches will be adopted in the EU and elsewhere, forest carbon storage is likely to play an important role in any cost-effective climate change abatement strategy.

We have presented a way to study economically optimal carbon storage in forestry without limiting the analysis to either even-aged or uneven-aged forestry. By determining the optimal management regime endogenously, we can cover both regimes simultaneously and analyze the effect of carbon storage on the optimal choice between them. Our carbon storage formulation takes into account carbon both stored in and released from dead tree matter and timber products. We show that higher stand density, long rotations and a possible switch to continuous cover management, with an emphasis on harvesting large trees with a high sawlog ratio, represent the economically efficient methods to decrease net carbon emissions. Optimal regime shifts between clearcutting and continuous cover forestry in size-structured stands have not been previously addressed in the carbon storage literature. The importance of our results is further emphasized by recent arguments that forests heterogeneity (age, size and species structure) may improve forest resilience under disturbances caused by climate change (Gamfeldt et al. 2015, Gauthier et al. 2015). The next step, then, will be to extend our generalized approach to multi-species forest stands.

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