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

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Abstract

Carbon storage in forests can be increased to reduce carbon dioxide in the atmosphere. We use a joint production model of timber production and carbon sequestration to analyse the financially optimum silvicultural strategies for Scots pine and Norway spruce at the stand level in Finland. This study expands the earlier analyses by taking into account thinnings as measures to increase carbon stocks in forests, in addition to lengthening the rotation age. The results indicate that, in joint production, both the growing stock level and rotation length are increased, compared to pure timber management. The results show clearly the importance of including thinnings in the analysis. For Scots pine stands, a major share of the increase in average carbon storage during the rotation period was obtained by modifying thinnings while lengthening the rotation age had a minor impact, with carbon prices of 10 and 20 €/t CO_2. On the other hand, in the case of Norway spruce, delaying the clearcutting provided most of the increase in average carbon storage. The carbon tax/subsidy programme was found to increase discounted net revenues to the forest owners considerably. The carbon tax/subsidy programme had a positive impact on the average timber yield in a fully regulated forest framework due to the considerable increase in the yield of sawlog, whereas the yield of pulpwood was somewhat decreased.
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1. Introduction

Forests can be used to mitigate climate change by increasing the amount of carbon in forests. Carbon sequestration may become one of the major services that forests provide. In this situation, the forest manager faces the task of optimizing the joint production of timber and carbon sequestration, and possibly other non-timber benefits.

In environmental policy, carbon services can be administered in different ways. Project based approaches that identify carbon flows in a restricted area for a given time period are seen as viable instruments. Governments may employ tax and subsidy based instruments to reduce the total costs of meeting emission targets. One possibility is that participating forest owners are paid for the

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carbon they sequester into their forests, to help a nation to meet its emission targets. Thus, it might be profitable for forest owners to give up some timber returns in exchange for CO_2 returns. Another alternative is to use regulative approaches, e.g., to modify forest management regulations, where in use, in order to increase carbon sequestration.

The amount of carbon sequestration depends on the level of growing stock, which in turn is mainly influenced by intermediate as well as final cuttings and the initial regeneration investment. The rotation length approach has been commonly used to assess interactions between forestry and carbon sequestration. A usual approach to the question has been to solve the problem of production of timber and carbon sequestration analytically and then provide numerical examples based on a univariate or stand-level growth model for timber and tree carbon (see, e.g., Van Kooten et al., 1995; Hoen and Solberg, 1997; Gong and Kriström, 1999; Stainback and Alavalapati, 2002). A general impact reported in several studies and summarized in Watson et al. (2000) is the lengthening of the rotation. Hoen and Solberg (1994) is a forest-level optimization analysis which for each forest compartment in the analysis has several thinning schedules to choose among. However, a detailed study of trade-offs between stand management options such as thinning rate vs. final harvest age or the optimum timing and intensity of thinnings requires stand level analyses.

More detailed models of stand development have been used in a simulation setting to analyse rotation length effects on carbon flows and timber returns (Pussinen et al., 2002; Liski et al., 2001; Masera et al., 2003). However, these studies do not include economic optimization and thinnings as a measure to increase carbon sequestration.

In this study, we expand the earlier stand-level analyses by including thinnings and thereby controlling the growing stock to increase the amount of carbon sequestered. We determine the optimal combination of thinnings and final harvest age for joint production of timber and carbon sequestration, when carbon uptake is subsidized and carbon released is taxed. The impacts of compensation for carbon sequestration on the net present value of incomes from timber and carbon sequestration for forest owner are examined. Also, we report the average timber yield impacts in a fully regulated forest framework. Section 2 presents the joint production model and describes the stand data used in the

analysis. In Section 3, the results of model optimizations are shown. Section 4 presents the conclusions and discusses about the results.

2. Joint production model, parameter values and stand data

2.1. Including carbon sequestration in optimization

To simultaneously investigate carbon sequestration and timber management questions, we need an optimization model that contains intermediate cuttings and rotation as decision variables, and accounts for carbon flows. The model optimizes the timing and intensities of precommercial and commercial thinnings, and the rotation length.

Economic incentives to increase the amount of carbon sequestered are provided with a carbon subsidy/tax programme in our study. As sequestration provides a positive externality, forest owner receives a subsidy. On the other hand, a negative externality due to release of carbon at harvest is taxed. A similar crediting scheme is used, e.g., in Van Kooten et al. (1995) and in Hoen and Solberg (1997). However, in this analysis, we assume according to Kyoto Protocol the more simple case that all the carbon is released to the atmosphere immediately after harvesting, excluding thus the carbon storages in wood products. Also according to Kyoto Protocol, total belowground biomass expansion factors including coarse and small roots are applied to convert stem volume to total dry weight biomass volume.

The objective function (1) for the forest owner/manager maximizes the discounted net returns over an infinite time horizon with rotation age T and includes (at time t, whenever there is a cut) road-side value returns from intermediate and final cuts h_t, logging costs l_t, emission tax et_t, regeneration costs w and carbon subsidy cs_t, all discounted at rate r. For the years without a cut, h_t, l_t and et_t are equal to zero.

$$\max \pi = \left[\sum_{t=0}^{T} (h_t - l_t - et_t)(1+r)^{-t} - w + \sum_{t=0}^{T} cs_t(1+r)^{-t} \right] \frac{1}{1-(1+r)^{-T}}$$

(1)

In Eq. (1), the first summation refers to revenues and costs related to cuts: road-side sales returns (sawlogs and pulpwood) less harvesting costs and emission costs. The second summation accounts for payments for carbon

sequestration and is based on stand volume growth. These carbon revenues are assessed every 5 years based on the change in stem volume. Hence, for other years, the value of cs_t is equal to zero. The interest rate was the same in all discounting.

2.2. Forest rotation and thinning optimization model

The SMA software (Valsta and Linkosalo, 1995; Hyytiäinen et al., 2005) was augmented by carbon accounting to perform the analyses. Non-linear, non-differentiable optimization (Hooke and Jeeves, 1961) is utilized to find the optimum thinning and rotation solutions. The algorithm is complemented by random search phases at the initialization of restarts and after locating a candidate optimum solution, as described in Valsta (1992).

Following Roise (1986), Valsta (1987, 1992, 1993) and Haight and Monserud (1990), the optimization problem is formulated as a static, non-linear programming problem in the control variable space:

$$\max_{\mathbf{u}} \quad g(\mathbf{u}|\mathbf{x}_0) \tag{2.1}$$

subject to:

$$\mathbf{u} \in U \tag{2.2}$$

$$\mathbf{x}_0 \text{ given} \tag{2.3}$$

where $g: R^n \times R^m \to R$ is the objective function (Eq. (1)) that computes the net present value as in Eq. (1) based on initial stand state $\mathbf{x}_0 \in R^m$ and control variables $\mathbf{u} \in R^n$. The control variable vector $\mathbf{u}$ consists of the time to the first thinning, times between thinnings and intensities of thinnings, and the time to the final harvest after the last thinning. The number of thinnings is set exogenously for each optimization. Runs are repeated for several numbers of thinnings, and the number of thinnings that provides the optimum is chosen.

The stand projection system in SMA is based on individual-tree, distance-independent growth and mortality models (Hynynen, 1993, 1995a,b,c), also used in the Finnish MELA system (Siitonen et al., 1996) for national timber resource projections. Timber returns are computed by deducting logging costs from road-side values as in Valsta and Linkosalo (1995). Amounts of wood assortments are predicted with models that use tree characteristics (species, diameter, height) (Laasasenaho and Snellman, 1983). Harvesting costs are computed using the models by Kuitto et al. (1994). As input, these models use average tree size by species and tree type (sawlog tree, pulpwood tree), the amounts harvested by product classes and the amount harvested per hectare. Based on the input, the models compute productivity (m^3/h) in cut-to-length harvesting for felling and hauling.

2.3. Parameter values

The parameter values to be identified include biological and economic parameters. The price of carbon in the carbon subsidy/tax programme was assumed to be 10 €/ton of CO_2, or alternatively 20 €/ton of CO_2. The biomass expansion factors used in this study were 0.70510 Mg m^{-3} for Scots pine and 0.8139 Mg m^{-3} for Norway spruce (Lehtonen et al., 2004). The share of carbon in dry weight of biomass was assumed to be 0.5.

We used a 3% real discount rate. The road-side prices of Scots pine sawlog and pulpwood were 51 and 25 €/m^3, respectively. For Norway spruce sawlog and pulpwood, the prices were 45 and 33 €/m^3. The minimum size of a tree for sawlogs was 17 cm dbh and 12 m height. The sawlog price premium based on tree breast-height diameter was chosen to Finnish conditions based on Paajanen (1997). Regeneration costs were based on planting small seedlings with a cost of 1100 €/ha for Norway spruce and 600–1150 €/ha for Scots pine, depending on site conditions. These costs included all treatments up to the first commercial thinning.

The hourly harvesting cost rates were 67.23 € and 47.06 € for felling and hauling, respectively. Other fixed parameters were 200 m hauling distance, 20 m strip road distance, 4 m strip road width and the load sizes of 12.8 and 11.6 m^3 for sawlog and pulpwood load, respectively. Additionally, a minimum total cost of 420 €/ha was assigned for each harvest time and used if the total harvest costs would have been less. Parameter values for the optimization were: 10 for the number of optimization runs for each analysis, 300 points for the random search stages and 0.003 as the convergence criterion.

2.4. Stand data

Model computations starting from bare land were performed for 10 Scots pine stands and for 7 Norway spruce stands from southern and central Finland. The plots had undergone standard silvicultural treatments

Table 1
Main characteristics of the stands

Scots pine					Norway spruce				
Plot	Dominant height at year 100 (m)	Age (years)	Number of trees	Basal area (m^2/ha)	Plot	Dominant height at year 100 (m)	Age (years)	Number of trees	Basal area (m^2/ha)
1	20	41	1970	24.1	11	24	30	1700	26.3
2	22	41	1470	20.9	12	26	36	1825	29.3
3	22	27	1600	26.2	13	27	32	2250	29.9
4	22	24	2000	9.7	14	27	33	1825	26.6
5	23	33	1400	17.5	15	29	30	1800	24.9
6	24	29	1450	17.7	16	29	25	1400	20.5
7	24	25	2375	24.1	17	30	34	1700	26.5
8	24	22	1900	18.8					
9	24	34	2225	28.4					
10	25	33	2150	26.7					

but not thinnings prior to the age of measurement. Each stand projection is based on an initial tree list, obtained from a measured plot management. Most pine stands were regenerated by seeding, while all but one spruce stands were planted. The characteristics of these stands are given in Table 1.

3. Results

3.1. Optimal silviculture

3.1.1. Scots pine

The baseline in all analyses was the free optimum management maximizing discounted net returns over an infinite time horizon (the land expectation value). When applying the carbon subsidy/tax programme with a carbon price of 10 €/ton of CO_2, the rotation length was increased by 4–13 years in the Scots pine stands examined (Table 2a). This implies that clear-cutting would take place at the age of 71–104, instead of 62–96. The increases in the rotation period are not related to the initial rotation period. On average, clear-cutting was delayed by 9 years. Doubling the price of carbon increased the rotation length almost linearly, with an average increase of 21 years. Then, clearcutting took place at the age of 86–121.

In addition to rotation length, the carbon tax/subsidy programme affected the timing and intensity of thinnings. In our Scots pine stands, thinnings were postponed by approximately the same amount of years as clearcutting. The first thinning might, however, be delayed less. The intensity of the first thinning remained the same as in the base case, but other thinnings tended to be lighter, es-

pecially the last thinning. The optimal amount of thinnings for Scots pine remained four or five, even for carbon price of 20 €/ton of CO_2. A sample optimal cutting schedule for Scots pine is shown in Fig. 1.

The changes in optimal silviculture increased the average carbon storage during the rotation period by 42 tons CO_2/ha with carbon price of 10 €/ton of CO_2 and by 81 tons CO_2/ha with carbon price of 20 €/ton of CO_2 (Table 2a). The increases in average stand volume were 32 m^3/ha and 62 m^3/ha, respectively.

3.1.2. Norway spruce

For Norway spruce, clearcutting was postponed by 13–19 years compared to the base case with carbon price of 10 €/ton of CO_2 (Table 2b). The average increase in rotation length was 17 years. As the original rotation length varied between 58 and 69 years, the optimal rotation length with carbon policy was 71–86 years. Doubling the carbon price to 20 €/ton of CO_2 increased the rotation length more than linearly. The average

Table 2a
Rotation length, and average volume and average carbon storage during the rotation period for Scots pine

Carbon price (€/t CO_2)	0	10	20
Rotation length (years)	79 (62–96)	88 (71–104)	100 (86–121)
Average volume (m^3/ha)	116 (88–138)	148 (126–168)	178 (160–199)
Average carbon (t CO_2/ha)	150 (114–180)	192 (163–204)	231 (207–257)

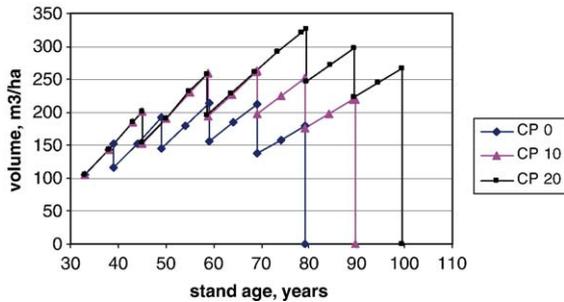Average values and distribution of values for stands examined.

Fig. 1. Optimal silviculture for Scots pine stand with carbon prices of 0, 10 and 20 €/t CO_2 (plot 5).

increase was 46 years, relative to the base case. The carbon tax/subsidy programme affected rotation length of Norway Spruce more than the one of Scots Pine. Thus, while in the base case the optimal rotation length for Norway Spruce was clearly shorter than for Scots pine, with carbon price of 20 €/ton of CO_2 the average rotation length for Norway spruce exceeded the one for Scots pine.

The optimal number of thinnings for Norway spruce increased from two to three or four, due to the longer rotation period. For most stands, the timing of first thinnings remained the same. The intensity of the second thinning was reduced moderately. A sample optimal cutting schedule for Norway spruce is shown in Fig. 2.

Changes in optimal silviculture increased the average carbon storage during the rotation period by 90 tons CO_2/ha with carbon price of 10 €/ton of CO_2 and by 236 tons CO_2/ha with carbon price of 20 €/ton of CO_2 (Table 2b). The increases in average stand volume were 62 m³/ha and 160 m³/ha, respectively. For Norway

spruce, doubling the price of carbon more than doubled the average carbon storage.

3.1.3. Importance of thinnings and rotation length when increasing carbon sequestration

Lacking in the earlier analyses that we are aware of, we also analysed the importance of modifying thinnings in increasing carbon sequestration, compared to lengthening the rotation age. For Scots pine, the carbon tax/subsidy programme affected both thinnings and the rotation length. The share of modifying thinnings in increasing carbon sequestration was evaluated by simulating separately the impacts of modifying either thinnings or rotation age on the average carbon storage. The separate simulations were based on the optimum solutions. This method provides only estimates but it was the only kind that our approach enabled. For most of the stands, these separate impacts however added up close to the total impact, generated by optimization. Although approximate, our analysis strongly indicated that delaying and lightening thinnings had a major contribution to increasing carbon sequestration and obtaining discounted incomes from carbon sequestration in the case of Scots pine. For most of the stands examined, 70–80% of the increase in the average carbon storage during the rotation period was obtained by modifying thinnings and only 20–30% by lengthening the rotation age, with a carbon price of 10 €/t CO_2. The results also indicate that to increase carbon sequestration it is more cost-effective to delay and lighten thinnings than to lengthen the rotation in the case of Scots pine. However, with thinnings, it is possible to increase carbon sequestration only to some extent, and the more carbon
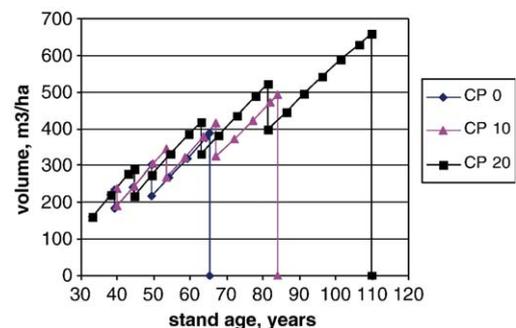
Table 2b
Rotation length, and average volume and average carbon storage during the rotation period for Norway spruce

Carbon price (€/t CO_2)	0	10	20
Rotation length (years)	64 (58–69)	81 (71–86)	110 (102–114)
Average volume (m³/ha)	145 (123–160)	207 (167–231)	305 (259–336)
Average carbon (t CO_2/ha)	219 (184–238)	309 (251–344)	455 (387–502)

Average values and distribution of values for stands examined.

Fig. 2. Optimal silviculture for Norway spruce stand with carbon prices of 0, 10 and 20 €/t CO_2 (plot 14).

Table 3a
Discounted net revenue from timber production, discounted revenue from carbon sequestration and discounted total net revenue for Scots pine, average for 10 stands

	Carbon price (€/t CO_2)		
	0	10	20
NPV timber (€/ha)	1156	1064	869
NPV carbon (€/ha)		998	2246
NPV total (€/ha)	1156	2061	3115
Change in NPV timber (%)		−8.0	−24.6
Change in NPV total (%)		78.3	169.5

is to be sequestered per hectare, the higher is the share of sequestration based on lengthening the rotation period.

Conversely, for Norway spruce, carbon crediting affected mainly the rotation length. Thus, lengthening the rotation period provided most of the increase in carbon sequestration. This is because, with Norway spruce, clearcutting can be delayed without a notable reduction in the volume growth rate and the volumes for mature stands are high.

3.2. Net revenues from timber production and carbon sequestration

3.2.1. Impacts on revenues for stands starting from the bare land

The carbon tax/subsidy programme was found to increase incomes to forest owners considerably, when starting from bare land. The average net present value of income was increased from 1156 €/ha to 2061 €/ha for Scots pine and from 1894 €/ha to 3140 €/ha for Norway spruce, with carbon price of 10 €/t CO_2 (Tables 3a and 3b). The income from carbon sequestration consisted of almost a half of the total

net present value income for Scots pine and Norway spruce, with carbon price of 10 €/t CO_2.

The forest owner could not however affect much the net income from carbon sequestration by changing the stand management. For Norway spruce stands in average, the joint income would increase from 1894 €/ha to 2980 €/ha even without any change in the silviculture, if carbon price were 10 €/t CO_2. As applying an optimal silviculture would increase the total NPV to 3140 €/ha, the additional benefit from modifying silviculture would be 160 €/ha. The results are similar for Scots pine stands.

Silviculture, that maximizes the joint discounted net income from both timber production and carbon sequestration, differs from a silviculture that maximizes the net present value from timber production. This implies that income from timber production is decreased. The loss in discounted net income from timber production was 8% for Scots pine and 10% for Norway spruce, with carbon price of 10 €/t CO_2. For carbon price of 20 €/t CO_2, the timber income reduced considerably more in the case of Norway spruce (−42%) than in the case of Scots pine (−25%). However, in the case of Norway spruce, a larger amount of carbon was sequestered.

The net CO_2 revenue and the timber returns have distinctly different time paths: the discounted net returns from CO_2 sequestration are mostly received already by mid-rotation while about half of the net timber returns come as late as at the time of the final harvest. Sample carbon and timber return time paths are shown in Fig. 3, depicting the discounted CO_2 revenues and costs as well as stumpage returns and regeneration cost at 3% interest rate.

Table 3b
Discounted net revenue from timber production, discounted revenue from carbon sequestration and discounted total net revenue for Norway spruce, average for 7 stands

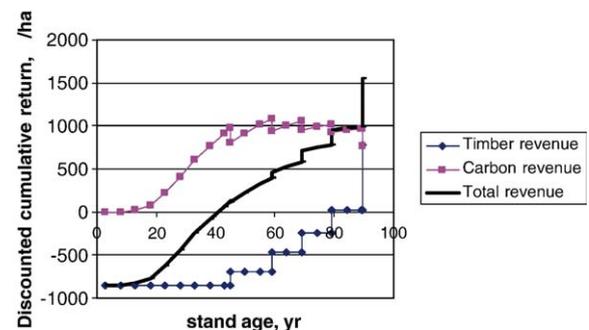|	Carbon price (€/t CO_2)		
	0	10	20
NPV timber (€/ha)	1894	1701	1095
NPV carbon (€/ha)		1439	3688
NPV total (€/ha)	1894	3140	4783
Change in NPV timber (%)		−10.2	−42.2
Change in NPV total (%)		65.8	152.6

Fig. 3. The discounted net cumulative values of CO_2 sequestration and timber production in a sample management regime, 3% discount rate.
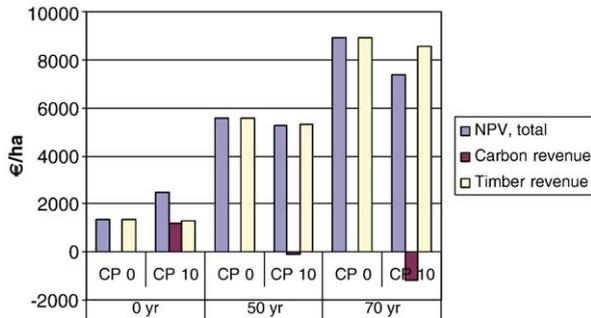
Fig. 4. Discounted total net revenue, discounted revenue from carbon sequestration and discounted net revenue from timber production for three different ages onwards (ages 0, 50 and 70), with carbon prices of 0 and 10 €/t CO_2 (Scots pine, plot 7).

3.2.2. Impacts on revenues from stands of various ages

The shares of timber and carbon income depend also on the age of stand, at which the carbon tax/subsidy scheme is started to apply. For stands starting from bare land, the net carbon income is positive as the amounts of carbon sequestered and released are equal and the incomes from sequestration are obtained first. For older stands, the total amount of carbon sequestered between starting the carbon tax/subsidy programme and clearcutting is lower than carbon released, and even after discounting the value of sequestration before and after clearcutting the net revenues from carbon sequestration become negative with increasing age.

The impact of the initial age of a sample Scots pine stand is demonstrated in Fig. 4 for the carbon price of 10 €/t CO_2. When starting from bare land, the incomes

Table 4a
Timber yield for Scots pine, average for 10 stands

Carbon price (€/t CO_2)	0	10	20
Timber yield, m^3/ha/year			
Sawlog	3.6	4.1	4.2
Pulpwood	1.9	1.7	1.5
Total[a]	5.6	5.8	5.8
Change relative to base case (no value for carbon), %			
Sawlog		12.5	17.3
Pulpwood		−8.6	−19.6
Total		5.2	4.7

[a] Waste wood is not included, that implies that sawlog and pulpwood do not add up to total.

Table 4b
Timber yield for Norway spruce, average for 7 stands

Carbon price (€/t CO_2)	0	10	20
Timber yield, m^3/ha/year			
Sawlog	4.4	5.4	5.8
Pulpwood	3.6	3.1	3.0
Total[a]	8.1	8.7	8.8
Change relative to base case (no value for carbon), %			
Sawlog		23.2	30.6
Pulpwood		−12.9	−16.6
Total		6.7	8.6

[a] Waste wood is not included, that implies that sawlog and pulpwood do not add up to total.

from carbon are equal to incomes from timber production in this example. On the other hand, forest owners that have older stands do not receive net incomes from carbon sequestration. For a 50-year-old stand, the net carbon income is zero and for the owner of a 70-year-old stand the discounted net carbon income is negative. This is due to fact that the forest owner has to pay for the release of carbon when clearcutting is made in this example in age of 81 years. On the other hand, carbon sequestration before clearcutting during those 11 years is quite small and the same applies for carbon sequestration right after clearcutting.

3.3. Impacts on mean annual timber yields

In this analysis, we are able to compare mean annual timber yields in two situations: in the original forests without carbon policy and in the new forests with carbon tax/subsidy programme when forest management has adjusted to the new policy.

The carbon tax/subsidy programme had a positive impact on the mean annual yield. Total timber yield of Scots pine was increased by 5% and of Norway spruce by 7%, with carbon price of 10 €/t CO_2 (Tables 4a and 4b). With carbon price of 20 €/t CO_2, the increases were 5% and 9%, respectively. The yield of sawlog was increased considerably due to longer rotation periods, especially in the case of Norway spruce as the rotation length was increased more than in the case of Scots pine. With carbon price of 20 €/t CO_2, the yield of sawlogs of Norway spruce was increased by 31%. On the other hand, the yield of pulpwood was decreased for both Scots pine and Norway spruce.

4. Discussion and conclusions

This paper provides an analysis of impacts of carbon tax/subsidy programme on Scots pine and Norway spruce stands in Finland. In addition to lengthening the rotation age, modifying the timing and intensity of thinnings were allowed as measures to increase carbon sequestration. Both subsidy on sequestration and tax on release of carbon provide incentive to delay harvests. Postponing the income from thinnings affects net present value of income more than postponing the clearcut, with given amount of harvests, due to discounting.

For Scots pine, the carbon tax/subsidy programme delayed both clearcutting and thinnings. The growing stock was increased also by lightening the thinnings. On the other hand, for Norway spruce, the carbon tax/subsidy affected mainly the rotation length. The positive impact of carbon tax/subsidy on rotation length has also been shown in previous literature both analytically and empirically by, e.g., Van Kooten et al. (1995) and Hoen and Solberg (1997). Their analyses takes into account the carbon storages in wood products, instead of assuming that carbon is released at the time of harvests, as we have done according to the current practice in Kyoto Protocol. Our practice implies slightly longer rotation ages as the discounted carbon payments due to release are larger. With a given price of carbon, a considerably larger amount of carbon was sequestered in case of Norway spruce than in case of Scots pine. In our data and in Finland in general, Norway spruce has greater stand volume and biomass, especially in mature stands. This is partly because Norway spruce occupies more fertile sites in Finland. Due to the resulting larger growth potential, stand and biomass can also increased in a more cost-efficient way, especially by delaying the final cutting. This implies that rotation length and average carbon storage of Norway spruce are affected more than of Scots pine by increased carbon prices. However, some optimum solutions for Norway spruce incorporated higher stocking levels than what exist in the data used in estimating the growth model (Hynynen et al., 2002) thereby making the result somewhat uncertain.

The results show clearly the importance of including thinnings when increasing carbon sequestration. For Scots pine, postponing and lightening thinnings had a major contribution in the increase in the average carbon storage during the rotation period with moderate increases of sequestration. For Scots pine, a 20-year increase of rotation period implied an increase of 80 tons CO_2/ha in average carbon storage. Kaipainen et al. (2004) reported an increase of 22 tons CO_2/ha when rotation length was shifted from 90 to 110 years. We obtained an increase of 20 tons CO_2/ha by shifting the rotation length from 79 to 100 years (with a carbon price of 20 €/t CO_2), but we found that an additional 60 tons CO_2/ha increase in the average carbon storage could be obtained by modified thinnings. For Norway spruce, we obtained an increase of 90 tons CO_2/ha by shifting the rotation period from 64 to 81 years with a carbon price of 10 €/t CO_2, while Kaipainen et al. (2004) reported an increase of 35 tons CO_2/ha from shifting the rotation length from 90 to 110 years. The difference is mainly due to the original rotation length, as our analysis was based on the optimal silviculture while in Kaipainen et al. (2004) the rotation length was based on the current silvicultural practices in Finland. Indeed, in Fig. 5 of Kaipainen et al. they reported an approximate increase of 70 tons CO_2/ha when rotation length was shifted from 60 to 80 years. Also, the growth models used differ.

A carbon tax/subsidy programme was found to increase discounted net revenues to forest owners considerably, when starting from bare land. Discounted income from carbon sequestration accounted for almost a half of the total net present value income for Scots pine and Norway spruce, with a carbon price of 10 €/t CO_2. However, the difference between discounted revenues from sequestration and tax payments on release is decreasing with stand age at which the tax/subsidy scheme is implemented. In our example of 70-year-old Scots pine stand, the discounted net carbon income was negative due to the near term cost when clearcutting. If carbon storages in wood products had been taken into account, the income loss would have been reduced. Income from timber production was decreased moderately for all stand ages. It has been discussed whether compensation should be paid for all carbon sequestration or only for additional sequestration beyond business as usual stand management. In the calculations presented here, a carbon subsidy/tax programme is applied for the whole amount of carbon sequestered, instead of compensating only for the additional sequestration. However, also the tax is paid for the all carbon released.

The carbon tax/subsidy programme had a positive impact on the average timber yield. Van Kooten et al. (1995) reached the same conclusion, for the most likely

range of parameters. The sawlog yield was increased considerably due to longer rotation period. On the other hand, the pulpwood yield was decreased. Stainback and Alavalapati (2002) obtained the similar results for yields of sawlog and pulpwood. In their analysis, the yield of sawlog increases even with high carbon prices. In our analysis, however, the average annual yield of sawlog is decreasing after a certain carbon price, as the average annual growth over the rotation starts to decrease due to increased rotation length.

The results for timber production indicate that there is not necessarily a trade-off between using forests as carbon sinks and proving timber for material substitution. If carbon sequestration into forests is credited, the forests may first serve as a carbon sink and in the long run they may also provide more timber for substitution. However, in the transition period, while forests serve as carbon sink, the timber supply is likely to decrease. Also, the pulp and paper industry might suffer from a decrease in pulpwood production over the long run. The price of timber was assumed to be exogenous, thus excluding the market mechanism and the implied feedback of change in timber price on optimal silviculture, carbon sequestration and timber supply. These are important issues of further research.

As the discount rate affects the optimum forest capital and, hence, the amount of biomass, we have evaluated the sensitivity of our results by applying discount rates 2% and 4%. With a lower discount rate than 3%, applied in the base case, the average carbon storage was considerably higher than in the base case, and vice versa. This was in line with Van Kooten et al. (1995) that has shown that the annual supply of carbon sequestration is very sensitive to the discount rate. The higher the average carbon storage was in the base case, the more costly it was to increase it. This implies that with low discount rates the carbon tax/subsidy programme increased the average carbon storage less than with high discount rates. Increases in the rotation length were not very sensitive to discount rate on average, the impacts however varied between stands even qualitatively. As carbon incomes were obtained in the earlier phase of the rotation than timber income, the share of carbon income in total income increased with increasing interest rate.

Regeneration investment was not an endogenous variable in our optimization, because our plot data was from 15- to 41-year-old stands. Taking more management actions as endogenous would, in principle, reduce

the costs of carbon sequestration to some extent as a result of increased flexibility in stand management. However, the results by Hyytiäinen et al. (2005) and Kuuluvainen and Valsta (2006, p. 74) suggest that increasing the number of trees in young stands bears a significant cost.

In this analysis, only the above-ground carbon was included. Liski et al. (2001) indicated that carbon stocks in soils do not necessarily increase when rotation period is lengthened, as for Norway spruce the shortest rotation length examined provided the largest soil carbon stock. On the other hand, Kaipainen et al. (2004) reported larger carbon stocks also for soils when rotation length was increased. If soil carbon stock is significantly reduced after the final harvest, including soil carbon in the analysis would tend to increase the optimum rotation. The effect would be analogous to the effect of regeneration costs on the optimum Faustmann rotation.

Monitoring and regulating forest rotation age seems the most practicable way of implementing payment schemes for carbon sequestration. Our results suggest that ignoring thinnings might increase carbon sequestration costs significantly. Perhaps a general regulation of cut would allow the forest owners to allocate cuts cost efficiently. Such a scheme naturally requires a well-developed forest legislation and practice.

We found significant differences in sequestration costs between species and stands. This suggests that a policy instrument should be carefully designed to minimize costs. Differences between species and sites require more studies in different geographical regions.

This analysis was based on optimizing the base case as well as the joint production. The rotation lengths applied in practice, based on the silvicultural recommendations, may however exceed the financially optimal rotation length (Hyytiäinen and Tahvonen, 2001). Hence, the changes from actual rotations might be unequal to those from optimum rotations. This should be kept in mind when considering our results for forest policy design.

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