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Costs of carbon sequestration in Scots pine stands in Finland

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Abstract

We use a joint production model of timber production and carbon sequestration to analyse the financially optimum silvicultural strategies and the costs of carbon sequestration for Scots pine at the stand level in Finland based on individual-tree growth models. 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 indicated that, in joint production, both the growing stock level and rotation length are increased. Postponing thinnings and reducing their intensity was more cost-effective in sequestering carbon than increasing the rotation length. The costs for moderate increases of carbon sequestration were rather low, with present values of 1 – 6 € /ton CO_2, and they depended on the amount of carbon sequestered, initial stand age, site, and growing stock characteristics. For mature stands, the present value of costs to sequester a given amount of carbon was considerably higher, exceeding 20 € /ton CO_2. This was due to the higher annual rate of carbon sequestration and the fact that all the additional sequestration had to be obtained by increasing the rotation length.

Keywords: carbon sink, climate change, forest management, mitigation, optimal silviculture

1. Introduction

Forests can be used to mitigate the climate change by increasing the amount of carbon in forests. Carbon sequestration may become one of the major services that forests provide. If carbon sequestration is an additional product of the forest, then 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 organized in different ways. Project based approaches that identify carbon flows in a restricted area for a given time period are seen as viable instruments. Because the Kyoto Protocol addresses nation-wide emissions, 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 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 the silviculture recommendations 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. An early study that covers a wide range of management practices is by Hoen and Solberg (1994). However, their forest-level analysis is not targeted towards detailed study of trade-offs between stand management options such as thinning rate vs. final harvest age.

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). An economic analysis with optimization has not been available for these kinds of models.

In this study we expand the earlier economic analysis 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 increasing carbon sequestration to various levels. Also, we highlight that the costs of carbon sequestration depend on initial stand age, site and growing stock characteristics, and the amount of carbon sequestered.

2. Joint production model

The forest owner faces two objectives, namely production of timber and carbon sequestration. 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 objective function (1) for the forest owner maximizes the discounted net returns over an infinite time horizon and includes (at time t) stumpage returns from harvests, h_t, logging costs, l_t and regeneration costs, w, all discounted at rate r for a rotation of T years, subtracted by the penalty function P (2) where V_t is stand volume at time t, V_s is the required average volume, and a and b are parameters of the penalty function

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

$$P = \begin{cases} a\left(V_s - \sum_{t=0}^{T}\frac{V_t}{T}\right)^b \; if\; V_s > \sum_{t=0}^{T}\frac{V_t}{T} \\ 0 \; otherwise \end{cases} \qquad (2)$$

The decision variables in our optimization are the timings and intensities of precommercial and commercial thinnings, and rotation length. Because the optimization model uses several dozens of state variables, we do not write out the state equations but refer to the description of the stand projection system later in this chapter.

To compute the economic effects of increased stocking levels and thus carbon sequestration, we added a penalty function which required that the stand management regime results in a given level of average growing stock over rotation. This permits the analysis of how to optimally achieve increased carbon stocks in the forest by adjusting thinnings and the final harvest.

An augmented version of the SMA software (Valsta and Linkosalo 1995) is used to perform these analyses. Nonlinear, nondifferential optimization (Hooke and Jeeves 1961) is utilized to find the optimum solutions. The algorithm is augmented by random search phases as described in Valsta (1992).

The stand projection system in SMA is based on individual-tree, distance-independent growth and mortality models (Hynynen 1993, 1995a, 1995b, 1995c), also used in the Finnish MELA system (Siitonen et al. 1996) for national timber resource projections. Timber returns are computed based on road-side values and logging costs 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).

The parameter values to be identified include biological and economic parameters. The road side prices of pine sawlogs and pulpwood were 51 and 25 €/m^3, respectively. 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 be representative to present Finnish conditions. Regeneration costs were based on planting small seedlings with a base case cost of 600-1150 €/ha, depending on site conditions. Each stand projection is based on an initial tree size distribution, obtained from a measured plot.

3. Data

Model computations starting from bare land have been performed for 13 Scots pine stands from Southern and Central Finland. The characteristics of these stands are represented in Table 1. Computations starting from various ages have been performed for four Scots pine stands of 24-36 (initial age of the plot), 50 and 70 years. The initial states of the stands for later ages were obtained by simulating the development of stand according to silvicultural recommendations of Forestry Development Centre Tapio.

Table 1 Main characteristics of the stands.

Stand	H_{100}	Age	N	BA
501	19	40	2730	19.75
533	20	41	1970	24.09
53	21	40	1525	22.76
801	22	24	2000	10.00
115	22	27	1600	26.18
24	23	33	1400	17.48
27	24	29	1450	17.66
34	24	25	2375	24.11
4	24	36	1750	24.12
38	25	33	2150	26.56
219	28	27	2096	23.62
60	28	28	1875	26.63
20	29	29	2325	26.91

4. Results

The cost estimates are based on model optimizations in which the amount of carbon sequestered has been increased exogenously by increasing the required average stem volume during the rotation period by 20 m^3/ha (corresponding the amount of 23 ton of CO_2/ha in whole tree biomass) or 40 m^3/ha (45 ton of CO_2/ha). Costs follow from the loss in present value of net revenue due to the additional constraint. We used a 3 % real discount rate.

4.1 Optimal silviculture

The increased carbon sequestration can be obtained in the model by postponing the final cut and thinnings and by changing the intensity of thinnings. Delaying the harvests reduces the present value of timber income due to the discounting. Postponing the income from thinnings affects the net present value of income more than postponing the final harvest. On the other hand, postponing the thinnings is likely to increase the average volume more effectively.

As an example, the optimum cutting schedule for plot 4 is given for the unconstrained case and the one with an increase of 40 m^3/ha (45 t CO_2/ha) in the average volume (Fig. 1). The rotation length was increased by 12 years. Also, all the thinnings were postponed by approximately 10 years, thus the intervals for thinnings remain the same. The intensity of thinnings was only slightly reduced, except in the case of the last thinning. Two third of the increase in the average volume was obtained with thinnings and only one third by changing the rotation length.

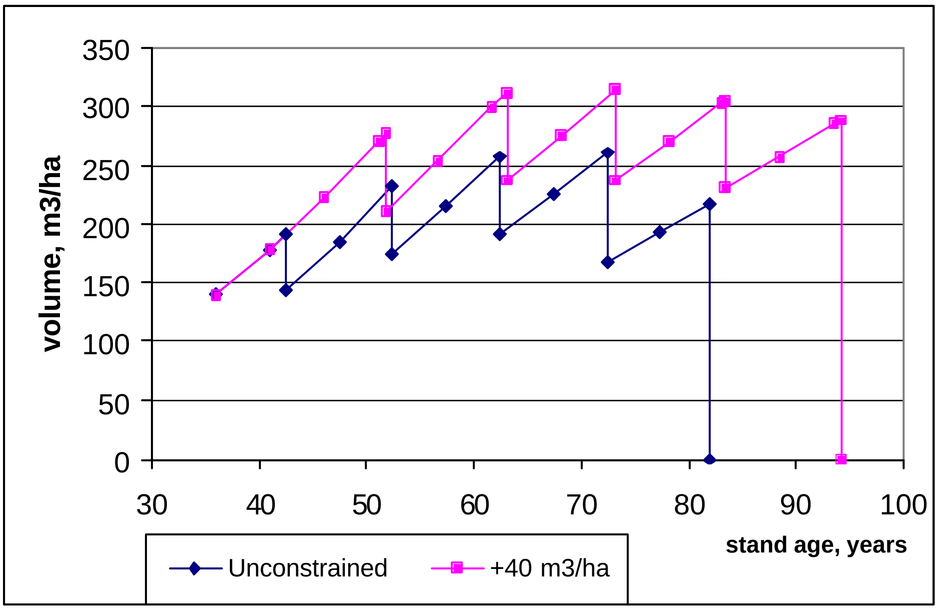

Figure 1 The impact of increasing the average stem volume by 40 m^3/ha (45 t CO_2/ha) on optimal silviculture.

4.2 Costs of carbon sequestration for stands starting from bare land

We show the average and marginal costs of carbon sequestration for plot 34 in Figure 2. As expected, the marginal costs increased when more carbon was sequestered as the least costly options to increase carbon sequestration are utilised first. Eventually, ecological factors set the limits to possibilities for increasing the average stem volume and thus the carbon sequestered.

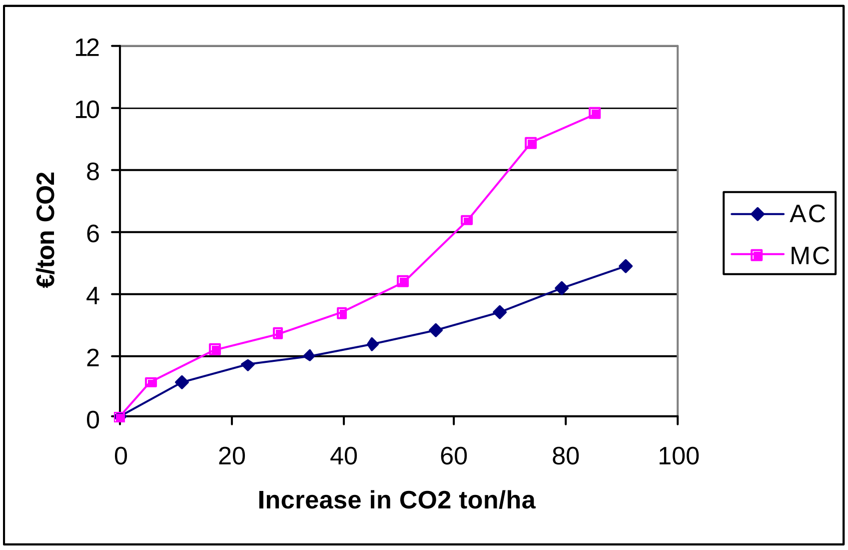

Figure 2 Present value average and marginal costs of carbon sequestration for plot 34.

Rotation age was increased from 70 years to 101 years for plot 34 when carbon sequestration was increased up to 90 ton CO_2/ha (Fig. 3). With small amounts of carbon sequestered, the larger share of carbon sequestered was obtained by postponing thinnings and reducing their intensity. However, with thinnings it is possible to increase the carbon sequestration only to some extent, and the more carbon is sequestered per hectare, the higher share of sequestration has to be obtained by lengthening the rotation period.

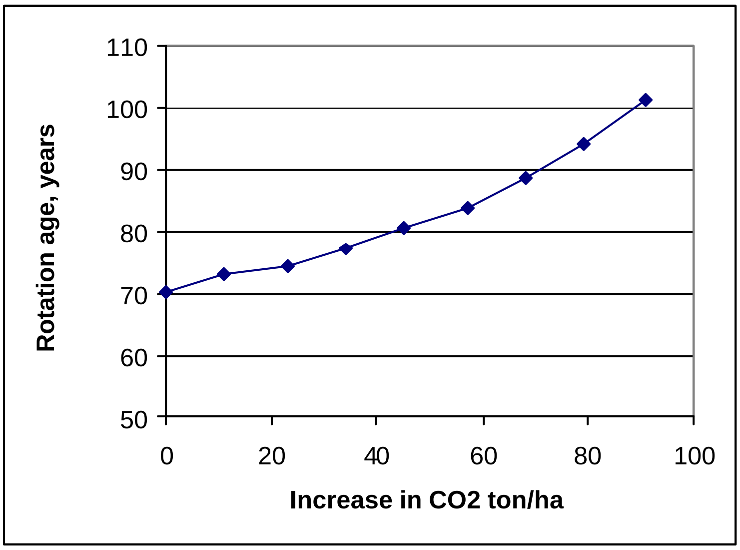

Figure 3 Impact of increasing carbon sequestration on rotation age for plot 34.

The tradeoff between the two objectives, namely timber production and carbon sequestration, can be described through production possibilities frontier analysis. The production possibility frontier of net present value of timber production and carbon sequestration for plot 34 is represented in Figure 4. Increasing carbon sequestration through the additional constraint reduces NPV. The shape of the production possibility frontier implies that it is optimal to use forests both for timber production and for carbon sequestration instead of using some stands for timber production and others for carbon sequestration. Convex combinations of points of the frontier are inferior.

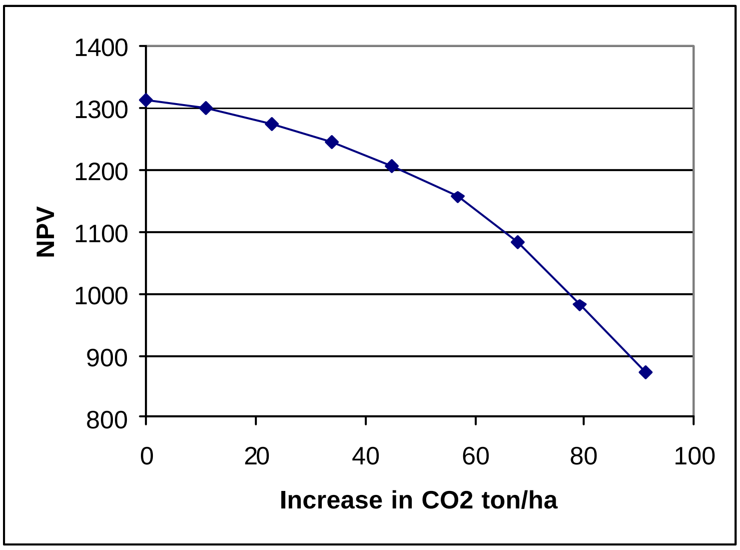

Figure 4 Production possibilities frontier of net present value of timber production and carbon sequestration for plot 34.

Costs differences between stands are illustrated in Figure 5 with results from a set of 13 individual plots and the average of these plots. The cost curves are obtained by increasing the average stem volume by 20 m^3/ha (23 ton of CO_2/ha) and 40 m^3/ha (45 ton of CO_2/ha).

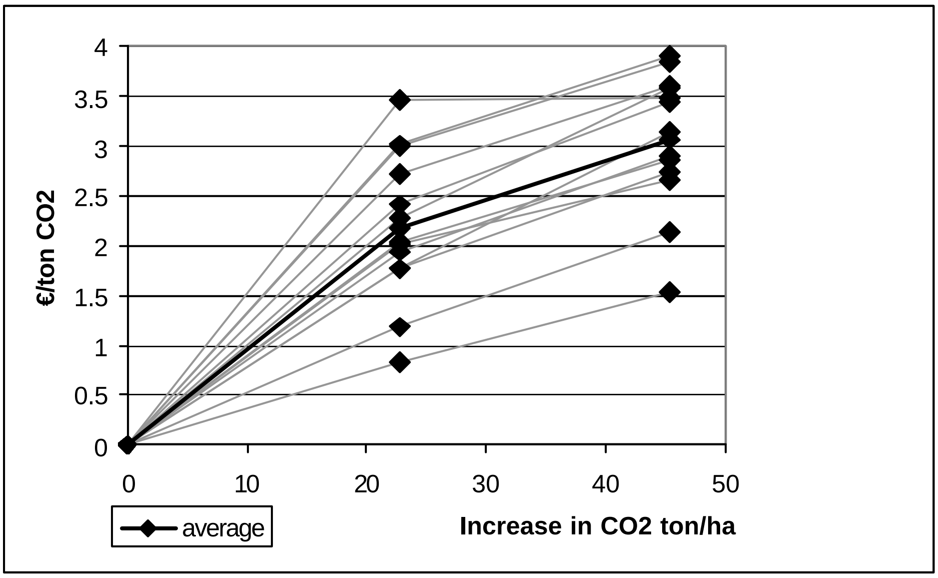

Figure 5 Present value average costs for a set of 13 individual plots and the average of these plots, €/ton of CO_2.

The costs differed notably between stands. For increase of 23 ton of CO_2/ha, the present value average cost varied from 0.8 €/ton of CO_2 to 3.5 €/ton of CO_2, with average of 2.2 €/ton of CO_2, and for increase of 45 ton of CO_2/ha from 1.5 €/ton of CO_2 to 3.9 €/ton of CO_2, with average of 3.1 €/ton of CO_2. However, about a half of the cost estimates were in a quite small range. No single factor explaining the cost differences between stands could been found. In order to analyse in which kind of forests it is less costly to increase sequestration more plots with more diverse properties are needed. Also, in order to make the stands more comparable, the initial age should be same.

4.3. Costs of carbon sequestration for stands of different ages

In addition of computations starting from bare land, we have performed computations for stands of various ages (24-36, 50 and 70 years). We increased the average volume by the same amount during the remaining rotation period for all of the plots of various ages. This implies that time period available for carbon sequestration (Table 2, second column) and thus the annual rate of increase in carbon sequestration (Table 2, third column) varies. The same average volume is required to fulfill during both the current and future rotation periods.

Table 2 The present value costs, sequestration periods and annual rates of carbon sequestration for stands of various ages, when increasing the average stem volume by 40 m^3/ha. All the figures represent average values of 4 stands.

Age class	Discounted cost €/ton CO_2 /ha	Sequestration period, years	Increase of CO_2, ton y^{-1} ha^{-1}	Rotation , years
Bare land	3.1	92	0.5	92
Stands of 24-36 years	5.1	57	0.8	87
Stands of 50 years	5.6	35	1.3	85
Mature stands (70 years)	17.7	20	2.3	90

For stands starting from bare land the time period available for increased sequestration of 45 ton of CO_2/ha was on average 92 years while for 70 year old stands the time period was only 20 years. Correspondingly, the average annual increase varied from 0.5 ton of CO_2 per ha per year for bare land stands to 2.3 ton of CO_2 ha^{-1-yr} for stands of 70 years. The impact of annual rate of carbon sequestration on unit cost is illustrated in Figure 6 and can be seen also in Figure 7.

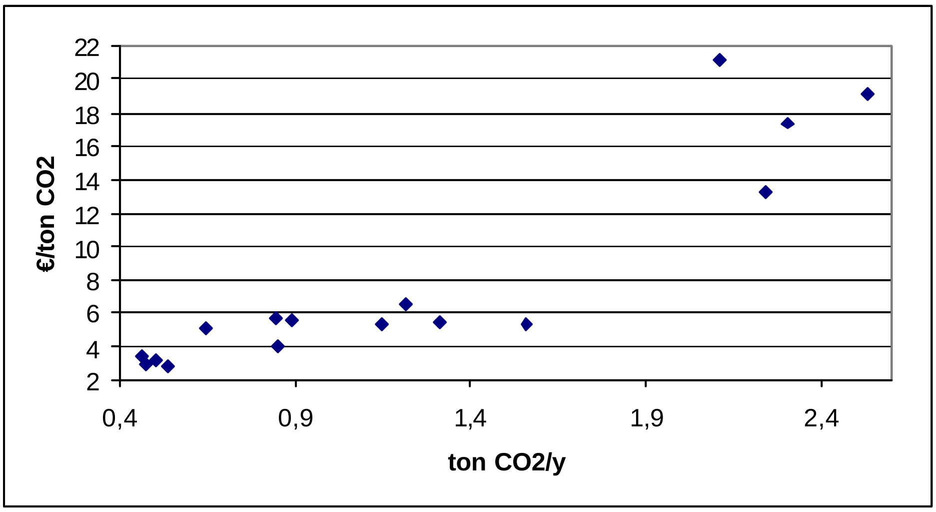

Figure 6 Present value costs of carbon sequestration in relation to increased sequestration per year.

As expected, the costs are the highest for 70 year old stands as the amount of carbon that have to be sequestered per year is largest. In addition of higher annual sequestration, higher costs are explained by the fact that regulating thinnings is no more an economically viable way to affect carbon sequestration. Thus sequestration can be increased only by lengthening the rotation that is more expensive measure than postponing thinnings. For younger stands, carbon sequestration takes mainly place between the years 40-70 by delaying and reducing thinnings. Also, for older stands the NPV's are higher as the discounting period is shorter. Thus, the loss calculated in absolute terms is higher.

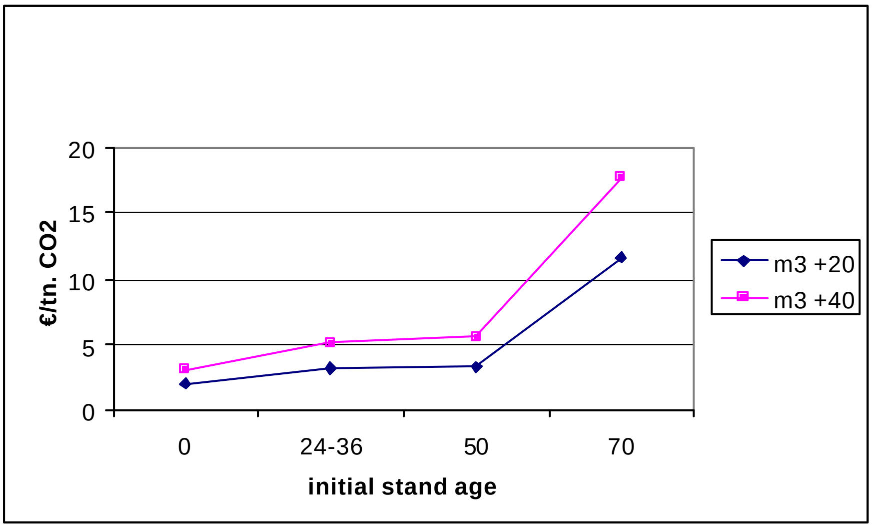

Figure 7 Average present value costs of carbon sequestration for different initial stand ages.

Even though carbon sequestration starts before 50 years of age, the costs are approximately the same for young stands and for 50 year old stands. As mentioned, the state of the stands at later ages were obtained by simulating them according to silvicultural recommendations of Tapio, to illustrate the state of the Finnish scot pine stands in a reality. This implied that the 50 year old stands were thinned right before starting to increase the carbon sequestration. The stands of 50 years and mature stands might provide higher costs for carbon sequestration if earlier thinnings were simulated at lower intensity. Correspondingly, the younger stands might provide different unit costs if an initial volume were lower. As illustrated in Figure 8, if the initial basal area differs from the one resulting from silvicultural recommendations (BA 19), higher unit costs of carbon sequestration are obtained. Higher initial basal area may diminish the biological potential and thus marginal revenue. Correspondingly, for the stands of lower basal area it may be difficult to increase the volume and thus carbon sequestration in absolute terms, due to lower growth potential of the initial stand. As the costs depend on whether thinnings have already been practiced or are still to be done, age of the stand for starting the carbon sequestration policy is an essential factor.

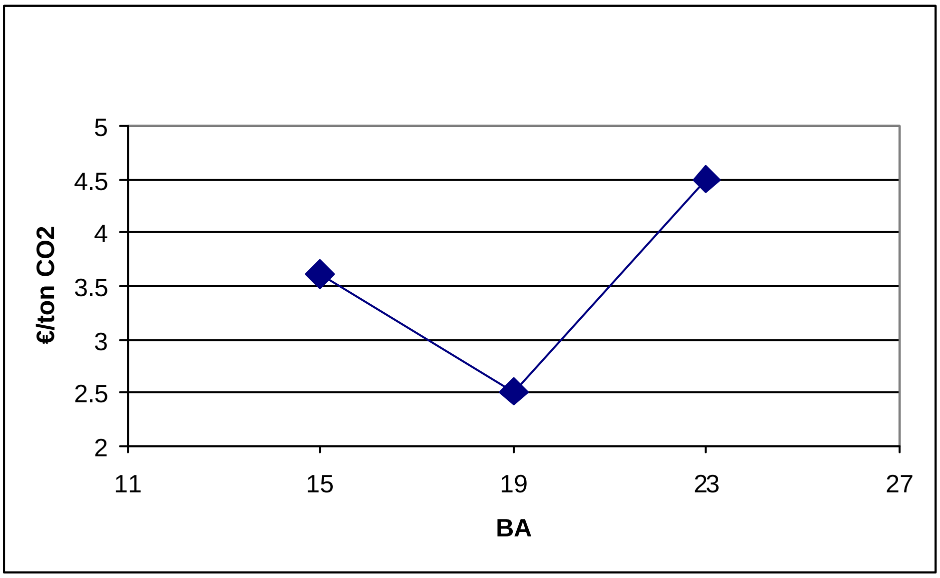

Figure 8 Present value unit costs of carbon sequestration for a 50-year old stand of various simulated initial basal area levels (15, 19 and 23), increase in average stem volume 20 m^3/ha.

5. Conclusions

This paper provides a preliminary analysis of costs of carbon sequestration for Scots pine stands in Finland. In addition of lengthening the rotation age, modifying the timing and intensity of thinnings were allowed as measures to increase carbon sequestration. Preliminary results suggest that postponing thinnings and reducing their intensity would be even more cost-effective measure to sequester carbon than increasing the rotation length. However, the more carbon is sequestered per hectare, the higher share of sequestration has to be obtained by lengthening the rotation period.

The results demonstrated that the cost of carbon sequestration is rather low with moderate amount of carbon sequestered, with a present value of 1 – 6 € /ton CO_2 depending on amount of carbon sequestered, initial stand age, site, and growing stock characteristics. As expected, marginal costs were an increasing function of the amount of carbon sequestered.

In this study we illustrated how the costs depend on the annual rate of additional carbon sequestration. For mature stands, the present value of costs to sequester a given amount of carbon were considerably higher than for younger stands, exceeding 20 € /ton CO_2. In addition of higher annual rate of sequestration, the higher costs were explained by the fact that the only measure available for increasing sequestration was lengthening the rotation period. Also, for older stands the NPV's are higher as the discounting period is shorter and thus the loss calculated in absolute terms is higher. In further analysis we plan to fix the annual amount of carbon sequestered in order to better analyse the impact of stand age and state on costs.

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References

GONG, P. AND B. KRISTRÖM, B. 1999. Regulating forest rotation to increase CO_2 sequestration. SLU (Sveriges Lantbruksuniversitet), Institutionen för skogsekonomi, Arbetsrapport 272.
HOEN, H.F. AND B. SOLBERG, B. 1994. Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. Forest Science 40 (3): 429-451.
HOEN, H.F. AND SOLBERG, B. 1997. CO_2-taxing, timber rotations, and market implications. Critical Review in Environmental Science and Technology, 27 (Special), 177-184.
HOOKE, R. AND JEEVES, T.A. 1961. "Direct search" solution of numerical and statistical problems. J. Assoc. Comput. Mach. 8:212-229.
HYNYNEN, J. 1993. Self-thinning models for even-aged stands of Pinus sylvestris, Picea abies and Betula pendula. Scandinavian Journal of Forest Research 8(3):326-336.
HYNYNEN, J 1995a. Modelling tree growth for managed stands. Finnish Forest Research Institute, Research Papers 576.
HYNYNEN, J. 1995b. Predicting the growth response to thinning for Scots pine stands using individual-tree growth models. Silva Fennica 29(3):225-246.
HYNYNEN, J. 1995c. Predicting tree crown ratio for unthinned and thinned Scots pine stands. Canadian Journal of Forest Research 25(1):57-62.
LAASASENAHO, J. AND SNELLMAN, C.-G. 1983. Männyn, kuusen ja koivun tilavuustaulukot. [Volume tables for Scots pine, Norway spruce and birch, in Finnish]. Metsäntutkimuslaitoksen tiedonantoja 113. 91 p.
LISKI J, PUSSINEN A, PINGOUD K, MÄKIPÄÄ R, AND KARJALAINEN T. 2001. Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research 31 (11): 2004-2013.
MASERA O R, GARZA-CALIGARIS, J.F., KANNINEN, M., KARJALAINEN, T., LISKI, J., NABUURS, G.J., PUSSINEN, A., DE JONG, B.H.J. AND MOHREN, G.M.J. 2003.Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. Ecological Modelling 164(2-3):177–199.
MONONEN, J.2002.Hiilensidonnan kustannukset ja hiilikompensaation vaikutukset metsänkasvatuksen edullisuuteen ja metsänhoitoon eteläsuomalaisissa männiköissä (The costs of carbon sequestration and the effect of compensation for carbon on profitability of forestry and on forest management in pine forests located in southern Finland). In Finnish. Master's thesis. University of Helsinki, Department of Forest Economics.
PUSSINEN, A., KARJALAINEN, T., MÄKIPÄÄ, R., VALSTA, L. AND KELLOMÄKI, S. 2002. Forest carbon sequestration and harvests in relation to applied rotation lengths under different climate and nitrogen deposition scenarios. Forest Ecology and Management 158: 103-115.
STAINBACK, G. A. AND ALAVALAPATI, R. R. 2002. Economic analysis of slach pine forest carbon sequestration in the southern U.S. Journal of Forest Economics 8(2):105-117.
SIITONEN, M., HÄRKÖNEN, K., HIRVELÄ, H., JÄMSÄ, J., KILPELÄINEN, H., SALMINEN, O. AND TEURI, M. 1996. MELA handbook, 1996 edition. Finnish Forest Research Institute, Research Papers. 452 p.
VAN KOOTEN, C., BINKLEY, C. AND DELCOURT, G. 1995. Effect of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services. American Journal of Agricultural Economics 77, 365-374.
VALSTA, L. 1992. An optimization model for Norway spruce management based on single-tree growth models. Tiivistelmä: Kuusikon käsittelyn optimointi puittaisiin kasvumalleihin pohjautuen. Acta Forestalia Fennica 232, p. 1-20.
VALSTA, L. AND LINKOSALO, T. 1995. Forest stand management and climate change - optimization analysis with a graphical user interface. Proceedings: Decision Support - 2001 Conference, Toronto, Canada, 12-16.9.1994, edited by J.M. Power, M. Strome and T.C. Daniel. American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland. pp 599-612.
WATSON, R T, NOBLE, I.R., BOLIN, B. RAVINDRANATH, N.H, VERARDO, D. J. AND DOKKEN, D J. 2000. IPCC Special Report on Land Use, Land-Use Change And Forestry. Cambridge University Press.