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Modeling Carbon Sequestration and Timber Production in a Regional Case Study

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Forests make up large ecosystems and by the uptake of carbon dioxide can play an important role in mitigating the greenhouse effect. In this study, mitigation of carbon emissions through carbon uptake and storage in forest biomass and the use of forest biofuel for fossil fuel substitution were considered. The analysis was performed for a 3.2 million hectare region in northern Sweden. The objective was to maximize net present value for harvested timber, biofuel production and carbon sequestration. A carbon price for build-up of carbon storage and for emissions from harvested forest products was introduced to achieve an economic value for carbon sequestration. Forest development was simulated using an optimizing stand-level planning model, and the solution for the whole region was found using linear programming. A range of carbon prices was used to study the effect on harvest levels and carbon sequestration. At a zero carbon price, the mean annual harvest level was 5.4 million m^3, the mean annual carbon sequestration in forest biomass was 1.48 million tonnes and the mean annual replacement of carbon from fossil fuel with forest biofuel was 61 000 tonnes. Increasing the carbon price led to decreasing harvest levels of timber and decreasing harvest levels of forest biofuel. Also, thinning activities decreased more than clear-cut activities when the carbon prices increased. The level of carbon sequestration was governed by the harvest level and the site productivity. This led to varying results for different parts of the region.

Keywords boreal forest, carbon sequestration, forest biofuel, forest management planning, optimization

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1 Introduction

Forests make up large ecosystems that act as resources for different activities, such as timber production, biodiversity preservation and recreation. Lately, their role as carbon sinks has also received much attention. In extensively forested countries, forests can play an import role in mitigating anthropogenic carbon dioxide (CO_2) emissions. The mitigation can be done in three general ways: 1) carbon uptake and storage in forest biomass and forest soil, 2) substitution of fossil fuel with biofuel which is carbon neutral, and 3) substitution of wood products for more energy-demanding materials. In this study, aspects 1) and 2) are considered on a regional level, although the carbon storage in forest soil was not considered.

Sweden is extensively forested, which provides high potential for timber and forest fuel production and for using forests to mitigate anthropogenic CO_2 emissions. Productive forests cover 55% of the land area (productive is defined as growth over 1 m^3 per hectare per year) and contain 3 billion m^3 of timber. The annual forest growth is 104 million m^3 and the annual harvest 83.4 million m^3 (Statistical yearbook… 2004). Consequently, biomass harvest is significantly lower than biomass growth. The carbon stock on forest land in aboveground tree parts is estimated to be 630 million tonnes. The CO_2 emissions from fossil fuel were 54.8 million tonnes per year in 2002 (Feldhusen et al. 2004), but due to forest growth it is estimated that 40–60% of these emissions were fixed in forest biomass (Miljötillståndet i skogen 1999). However, this fixed CO_2 has decreased by almost 50% during the last part of the 1990s and the first years of the twenty first century, compared to the first part of the 1990s. This is because the net increase in tree biomass is getting smaller (Statistical yearbook… 2004). Most of CO_2 emissions come from the combustion of fossil fuels such as oil, coal and gas. The use of biofuels for generating energy, as a substitute for fossil fuels, has the advantage of carbon neutrality, meaning that no new CO_2 is released to the atmosphere when burning biofuels. The energy supply in Sweden in 2002 was 616 TWh (including conversion losses from nuclear power) of which approximately 37 TWh comes from forest biofuel (lye from the pulp industry is not included) (Energiläget 2003). Improving forest management with, for example, increasing and improving fertilization could double the potential harvest of forest biofuel (Börjesson et al. 1997). However, there is a conflict between using the forest for long-term carbon storage and, at the same time, producing biofuel (Kirschbaum 2003).

Since the 1980s the Swedish climate policy has been integrated into environmental and energy policy. In the 1990s, a number of actions were taken to reduce greenhouse gas emissions. Taxes on the use of fossil fuel due to CO_2 emission and subsidies for an increased use of biofuel and for the construction of wind power plants were introduced. Sweden has also ratified the Kyoto protocol for mitigation of greenhouse gases. Lately, the Forestry Board formulated a climate policy (Klimatpolicy för Skogsvårdsorganisationen 2003) where increased use of forest biofuel is preferred to sequestering carbon in forest biomass or in forest soils.

Assessment of carbon sequestration and forest management can be modeled on a regional level if suitable data are available. Such studies were made for other regions and countries. For example, a study for the whole of Germany (Karjalainen et al. 2002) showed that the German forest sector can sustain a carbon sink until 2050. The study was performed in two steps: first, forest growth was simulated with process-based models; secondly, these results were scaled up to country level using national forest inventory data. Hoen and Solberg (1994) analyzed how the economic efficiency of carbon sequestration in the forests of Buskerud County in Norway could be enhanced through silvicultural management. They used aggregated forest inventory data and a long-range forest management planning model to do the analyses. The most cost-efficient changes from current management were fertilization, avoiding release thinning in young growth and changes in clear-cutting priorities. Increasing constraints on carbon sequestration led to increased clear-cutting of older stands on good site classes when the real rate of discount was low (2% and 3%). Instead, if the rate was high (up to 7%) – that provides higher value for carbon sequestration in the near future – the clear-cutting of stands with low productivity increased. A study of the carbon balance in the forest sector in Finland showed that carbon is stored more efficiently in standing timber than in wood-based products (Karjalainen et al. 1995).

In Sweden, Ågren and Hyvönen (2003) have modeled the changes in carbon stores in Swedish forest soils. They found that the carbon budget was mostly governed by the distribution of Norway spruce and Scots pine within the country. Ericsson (2003) studied carbon accumulation and fossil fuel substitution under different rotation length in a region (Dalarna) in middle Sweden. He included carbon accumulation in both forest biomass and soil. It was shown that prolonged rotation length increased the carbon accumulation.

The above studies all included aspects of carbon pools and dynamics in the forest ecosystem, and aspects related to economic efficiency and climate change were included in some of them.

There are several reasons for studying forest management and carbon sequestration in a regional setting. One aspect is the set of specific conditions for each region, such as natural, geographical and social conditions. Another aspect that needs to be addressed is the variation within the region itself. However, when analyzing at this scale, it is probably not practicable to include all possible aspects and scales of carbon sequestration. Therefore, the assessment of results of other studies is essential. As mentioned above, there are studies covering the whole of Sweden (Ågren and Hyvönen 2003) and the region Dalarna (Ericsson 2003). These studies were, however, simulation studies with a few management alternatives and did not include economic aspects. The contribution from our study is the use of optimization instead of simulation, incorporating economic factors and presenting intraregional results.

The aim of this study was to model the potential of carbon sequestration combined with timber and forest biofuel production within a region in northern Sweden. The effects on these three components are presented and will give an indication of problems and options at a large scale.

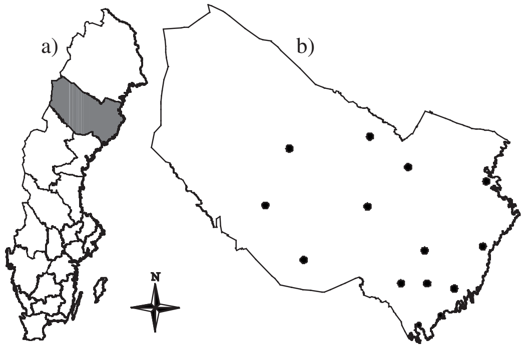

Fig. 1. a) Sweden and the county of Västerbotten (shaded area). b) Communities with potential biofuel plants that received biofuel in Västerbotten.

2 Material and Methods

2.1 The Study Area

The study was performed in the county of Västerbotten in northern Sweden (Fig. 1a). This county is rich in boreal forest dominated by Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula pendula* and *B. pubescens*), representing 45%, 36%, and 15%, respectively, of the total wood volume (Skogsdata 2004). The production potential varies within the county with the highest production at the coast, declining to the mountains in the west. The forest industry is concentrated towards the east, leading to high transportation costs for timber and pulpwood harvested in the western parts of the region. The present annual gross harvest in Västerbotten is around 7 million m^3 (Statistical yearbook… 2004) and the annual growth is approximately 9 million m^3 (Skogsdata 2004).

Detailed forest data for Västerbotten County were available through the National Forest Inventory (NFI). The Swedish NFI is an annual systematic field sample of circular plots located in square sample clusters. Temporary (radius 7 m) and permanent (radius 10 m) plots are used (Ranneby et al. 1987). In this study 3308 temporary and permanent plots located on productive forest land inventoried between 1996 and 2000 were used. The total area of the forestland represented by these plots was 3.2 million hectares.

2.2 Calculations

The analyses used a model presented and comprehensively described in Backéus et al. (2005). In brief, the model is an optimization model that maximizes the net present value (NPV) of wood production and carbon sequestration. Included components in the model were wood harvesting, extraction of harvest residues for biofuel production, transportation cost for biofuel, timber and pulpwood, the value of carbon fixation and the estimated cost of carbon emissions from forest products. The components were all included in the objective function (Eq. 1). The planning horizon was 100 years.

$$\text{Maximize } Z = NPV^{\text{wood}} + NPV^{\text{biofuel}} + PV^{\text{C-storage}} - PV^{\text{transport}} - PV^{\text{C-emission}} \quad (1)$$

where

NPV^{wood} = NPV of timber and pulpwood production, including silvicultural costs,

NPV^{biofuel} = NPV from extracted harvest residues (for biofuel), including transportation costs,

$PV^{\text{C-storage}}$ = present value of carbon storage,

$PV^{\text{transport}}$ = present value of transportation costs for timber and pulpwood,

$PV^{\text{C-emission}}$ = present value of the cost of carbon emissions from products.

The model was a linear programming (LP) model and was solved with a commercial solver (ILOG CPLEX 8.0) (ILOG Inc, Incline Village, NV, USA). The problem was to determine, for each treatment unit, a management program such that the overall objective function value was maximized subjected to a set of constraints.

At a regional level, one constraint regulated the ending inventory so that the standing volume after harvest in the last period was not allowed to be lower than the standing volume in the first period. Other constraints regulated the harvest flow, so that the maximum difference between the harvest levels between two subsequent periods was, at the most, 1%. This was to mimic the historical harvest pattern. At the treatment unit level, the thinning grade was not allowed to exceed 30% of the stand basal area, and the ending inventory, in order to generate sound management, should not decrease below 100 m^3 per hectare at the time of the final harvest (cf. Wikström and Eriksson 2000). The lowest age for clear-cutting was set according to the Swedish Forestry Act (Skogsvårdslagen – Handbok 2003). The calculations were done for 20 five-year periods and the real interest rate was set at 3%.

An optimizing stand-level management model presented by Wikström and Eriksson (2000) and Wikström (2001) was used to generate management program alternatives for each plot. Each plot represented a treatment unit. A management program was a series of states, outputs and treatments over time. The model was run for each treatment unit, and in each run up to thirty of the best management programs was saved and later used as input in the LP-model. The stand-level model includes routines for assessing, regeneration, growth, thinning response, mortality, biomass production and harvest value. The optimization at stand level was the same as for the whole region. The optimization program works in combination with the growth-and-yield simulator to simultaneously find harvest periods and which trees to harvest in these periods. Proposals for management were generated by an iterative search process guided by Tabu search. Stand replacement actions were not part of the optimization. Instead, initial condition was simulated, using the Hugin young forest survey database (Elfving 1982). The calculation of biomass is described in more detail below due to its importance for carbon accounting.

The estimations of biomass were made by using functions of Petersson (1999). The functions depict biomass contents in stems, branches, needles, stumps and coarse roots. The decay of dead tree parts, above and below ground, was calculated with the functions presented by Harmon et al. (2000). The below ground tree parts were assumed to decay in the same manner as the aboveground tree parts. The biomass change in every period was calculated as the sum of the growth of living biomass minus the decay of dead biomass, harvested wood and natural mortality. The change was multiplied by 0.49, which is the proportion of carbon in the dry weight biomass (Ståhl et al. 2004). Positive carbon change was multiplied by a carbon price to achieve an economic value for carbon sequestration. Harvest of forest biofuel was only possible after a clear-cut and only on sites more fertile than lichen types, as recommended by the National Forestry Board (Rekommendationer vid uttag… 2001). Due to technical limits we assumed that 75% of the branches and 25% of the needles were extracted (cf. Skogliga Konsekvensanalyser 2000, Rekommendationer vid uttag… 2001, Ericsson 2003). Soil carbon was not included in the calculations. The amount of dead wood was set to zero at the start of the planning horizon, as the data set lacked information about dead wood.

Emission rates from harvested forest products was calculated in the same way as in Karjalainen et al. (1994) and Liski et al. (2001) but distribution factors for Swedish conditions were set according to Warensjö (1997). Emission rates were calculated for the product groups, timber and pulpwood, where emissions from pulpwood were assumed to be released faster than timber. Carbon, in products disposed to landfills, was assumed to be released to the atmosphere immediately. The emissions were treated as a cost that was discounted at the start of the planning horizon. The cost was identical to the carbon price described below.

The prices for timber and pulpwood were retrieved from the 2002 pricelist from the Forest Owners Organization in Västerbotten. The prices for forest biofuel were retrieved from the Statistical Yearbook of Forestry (2004). Harvested timber was assumed to be transported to local sawmills and pulpwood to the only pulp mill, which is on the coast. Transportation cost for timber and pulpwood was derived from Arvidsson and Holmgren (1999) and the Statistical Yearbook of Forestry (2004). Forest biofuel was assumed to be transported to the nearest community within the county with more than 2000 inhabitants (Fig. 1b). The transportation cost for forest biofuel was derived from Fridh (1993) and Andersson and Nordén (1996). Although not shown in the objective function (1), transportation cost of timber and pulpwood made up separate parts of the transport term with different distances to the pulp mill or the local sawmill (Eq. 2).

$$\text{Transportation cost (SEK per m}^3\text{)} = 12.38 + 0.38 \cdot \text{distance to the processor} \qquad (2)$$

If not stated otherwise, the results are based on the true transportation cost (Eq. 2). However, in practice, timber purchasers apply a different price setting to encourage timber harvesting in more remote areas; in such cases the cost of transport paid by the forest owner is only 0.20 SEK per cubic meter times the distance in kilometers to the processor and at most 44 SEK per cubic meter. This transport cost was taken into consideration in one of the model runs to assess the effects of today's price policy. Carbon emissions from transport were not included.

As mentioned previously, the use of forest biofuel is CO_2-neutral, which makes it possible to mitigate emissions from fossil fuel. To assess the magnitude of the mitigation effect, a conversion factor of 0.812 representing the carbon from fossil fuel replaced by carbon from forest biofuel was used. This number was derived from the assumptions that carbon in dry biomass was 49% (Ståhl et al. 2004) and the calorific value for harvest residues was 5.4 MWh per tonne. The conversion factor for 1 tonne of oil equivalents to energy (MWh) was 11.67 (Fridh 1993), and the carbon content in oil was 86% (Mörtstedt and Hellsten 1982).

3 Results

The model was run for a range of carbon prices. The Swedish CO_2 tax in year 2002 was 630 SEK (1 SEK = 0.11 EUR, September, 2005) per tonne of CO_2. This corresponds to a carbon price of 2310 SEK per tonne carbon. When entering this price in the model, no harvest at all occurred. Therefore a set of lower carbon prices was tested. The prices varied between zero and 1200 SEK per tonne carbon. Harvest ceased after about 1200 SEK.

3.1 Wood Harvest, Forest Biofuel, and Carbon Sequestration

Wood harvest levels as a function of carbon price showed a nonlinear response so that harvesting decreased slowly for low carbon prices but faster as the carbon prices increased (Fig. 2). The stand-

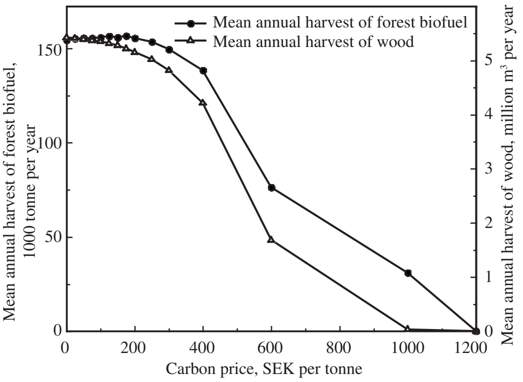

Fig. 2. Mean annual harvest of wood and forest biofuel for a 100-year period and for carbon prices between zero and 1200 SEK per tonne.

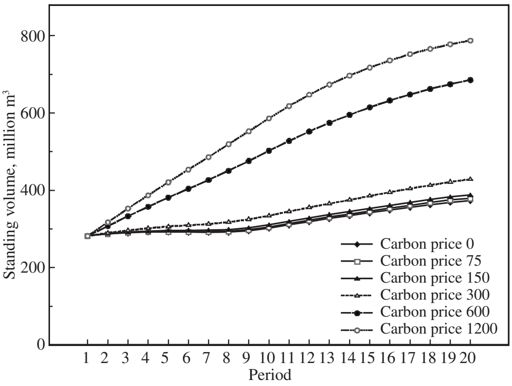

Fig. 3. Development of standing volume over time for carbon prices between zero and 1200 SEK per tonne carbon.

ing volume increased over time, and the increase was more pronounced for carbon prices over 300 SEK (Fig. 3). After the planning horizon of 100 years, the amount of dead wood (above ground parts, stumps and coarse roots) had grown to 63 million tonnes for zero carbon price and up to 89 million tonnes for the highest carbon price (1200 SEK) (Fig. 4). The increase pattern was different depending on price. The scenarios with the highest carbon prices, with almost no harvest, only have natural mortality and the dead wood storage is hence increasing at an almost constant rate. Harvest was performed for lower carbon prices and thereby harvest residues were generated. The stumps and coarse roots are included in the dead wood pool and are left after harvest and thus also

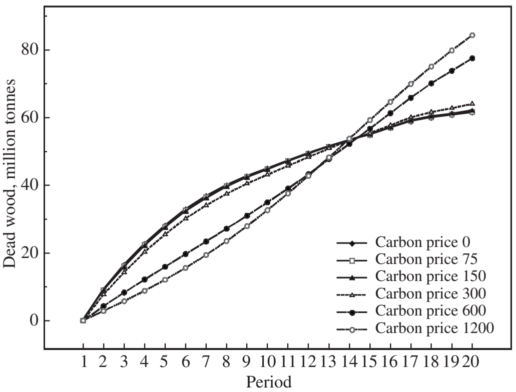

Fig. 4. Development of the stock of dead wood (above and below ground) over time for carbon prices between zero and 1200 SEK per tonne carbon. Note that no initial amount of dead wood was included as data was lacking.

accounted for. This lead to a fast increase of dead wood for the first half of the planning horizon. The amount of dead wood for carbon prices over 600 SEK was lower than the dead wood for the lower carbon prices for the first 70 years.

When the carbon price increased, the harvest activities in the western parts decreased relatively more than in the eastern parts although the decrease in absolute figures was uniform all over the county (Fig. 5). Details concerning how the maps were created are given in the Appendix. The mean annual harvest level of forest biofuel as a response to carbon price was ambiguous (Fig. 2), as opposed to the harvest level of wood which decreased strictly with carbon price. In fact, for carbon prices less than about 200 SEK per tonne, biofuel extraction increased with carbon price, which is explained by the harvesting from clear-cuts which increased somewhat under these prices (see below under Management implications). Furthermore, since biofuel harvest was only possible after clear-cutting, this led to an increase in biofuel extraction. For carbon prices above 200 SEK per tonne, biofuel extraction decreased with price, responding to price in the same way as wood harvesting. For carbon prices less than around 100 SEK per tonne the harvest of biofuel increased or was unchanged in most parts of the county compared to when no carbon price was applied. For higher carbon prices (more than

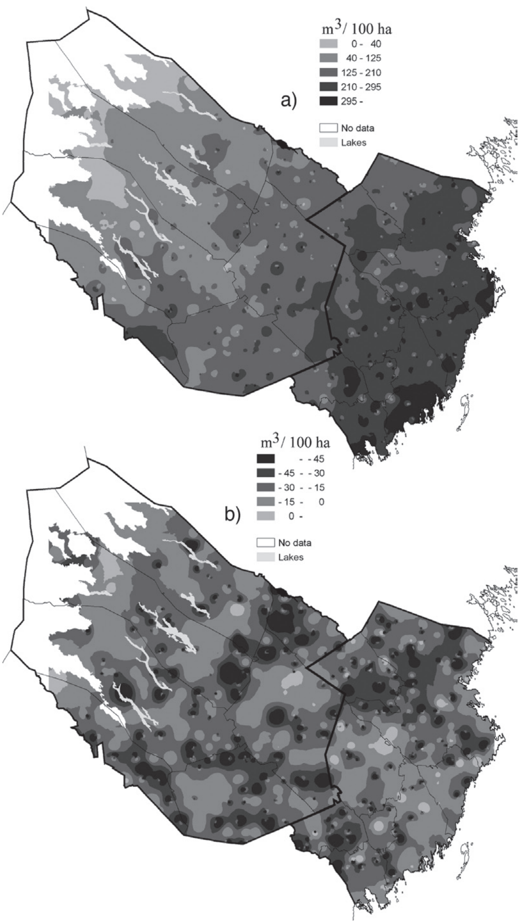

Fig. 5. Average harvest level (m^3 per 100 hectares per year) for carbon price zero, map a). The average value is a mean for all forest land, i.e., also for unharvested area. Map b) shows the reduction (in absolute values) in harvest level for carbon price 300 SEK per tonne. Notice that the legend classification is different for the maps.

about 200–300 SEK per tonne) biofuel harvest decreased all over the county although the relative decrease was larger in the western parts. In some parts of the county (mostly near the coast) the biofuel harvest was higher than in the scenario for zero carbon price (Fig. 6).

As expected, carbon sequestration increased with carbon price (Fig. 7). When the carbon price was zero, the carbon sequestration was highest in the eastern parts (Fig. 8). As the carbon price increased carbon sequestration did not follow the same geographical pattern as the harvest levels,

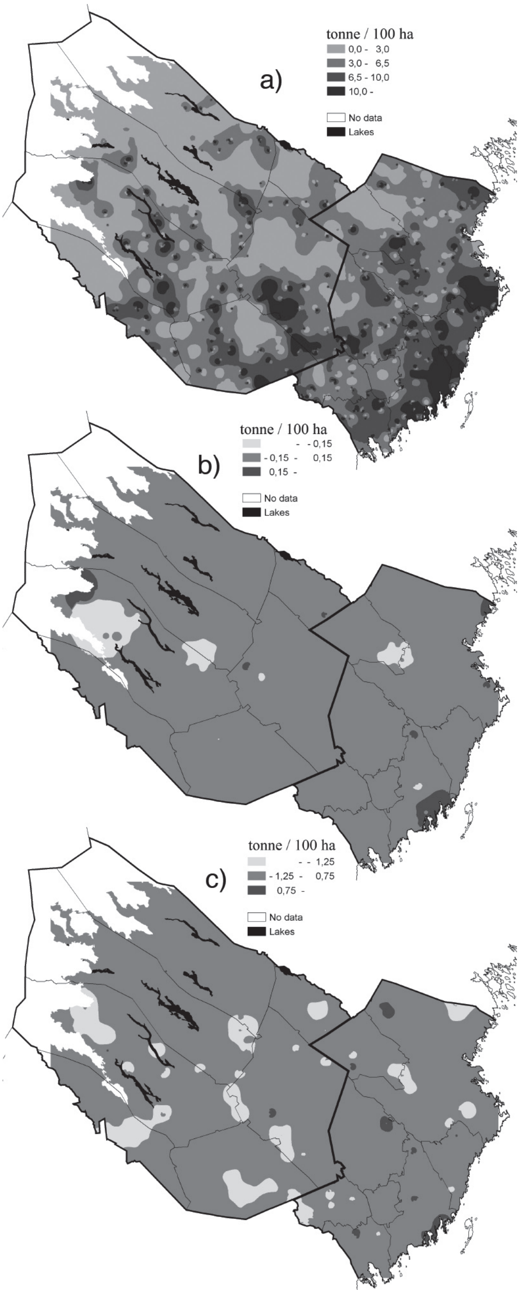

Fig. 6. Average biofuel harvest (tonne per 100 hectares per year) for carbon price zero, map a). The average value is a mean for all forest land i.e., also for unharvested area. Maps b) and c) show the change (in absolute values) in biofuel harvest for carbon price 75 [b)] and 300 [c)] SEK per tonne. Notice that the legend classification is different for all three maps.

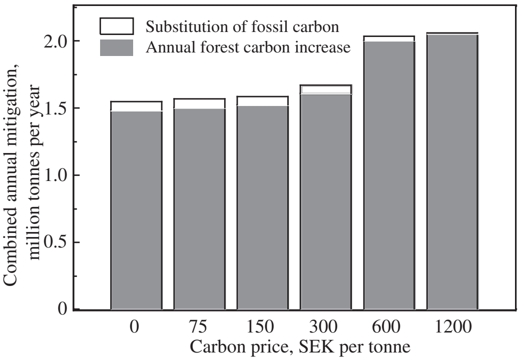

Fig. 7. Mean annual carbon mitigation effect from carbon sequestration in forest biomass and substituting fossil fuel with forest biofuel. Values are average for a 100-year period for carbon prices between zero and 1200 SEK per tonne.

but the relative increase was similar for almost the whole county. For carbon prices lower than 200–300 SEK per tonne, a small (a few percent) relative increase was present all over the county. For carbon prices higher than 600 SEK per tonne the relative increase was higher in the eastern and southern parts.

At a zero carbon price, substitution of fossil fuel for forest biofuel corresponds to 61 000 tonnes per year of fossil fuel carbon (Fig. 7). This corresponds to 4% of the total carbon sequestration and substitution, i.e., carbon sequestered in forest biomass plus substitution of carbon from fossil fuel. Although the total carbon mitigation was increasing with increasing carbon prices, the proportion that comes from biofuel decreased.

3.2 Management Implications

The proportion of thinning activity of the total harvested volume decreased as carbon price increased and timber harvesting decreased (Fig. 9), and consequently, the proportion of clear-cuttings increased. An effect of decreasing the thinning activity is that the standing volume increases and more carbon is stored in the forest. The thinnings decreased all over the county but the decrease was generally larger in the western parts. For carbon prices up to about 250 SEK per tonne of carbon the decrease in thinning activity

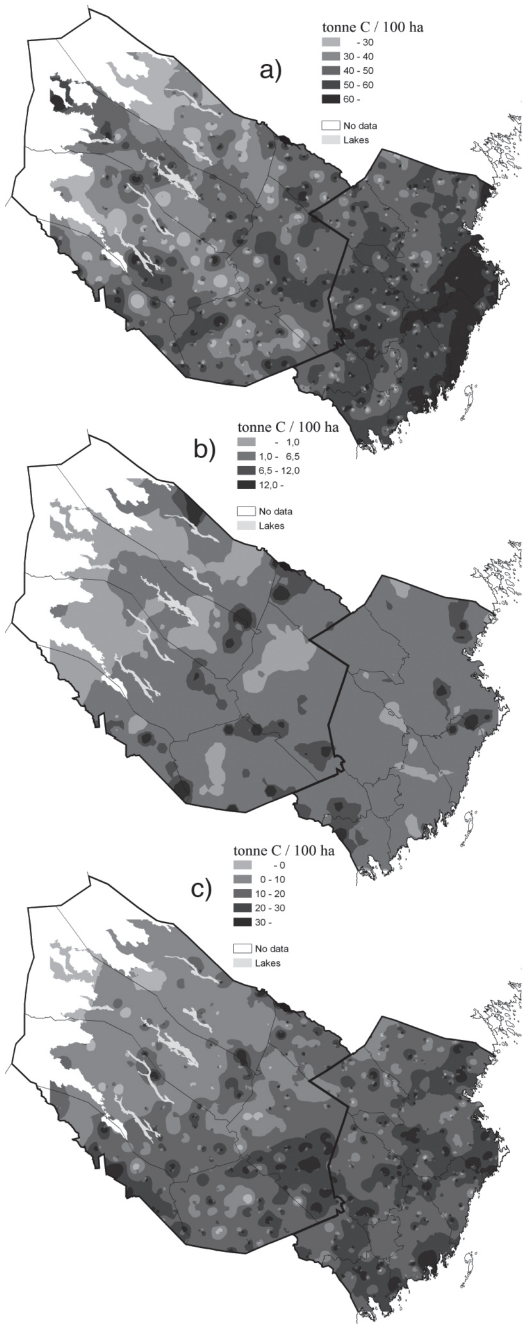

Fig. 8. Average carbon sequestration (tonne per 100 hectares per year) for carbon price zero, map a). Maps b) and c) show the increase (in absolute values) in carbon sequestration for carbon price 300 SEK per tonne [b)] and 600 SEK per tonne [c)]. Notice that the legend classification is different for all three maps.

Table 1. Differences in net present values, harvest levels and carbon storage for different transportation costs and carbon price set to zero.

	Transportation cost	
	Current (with upper limit)	True (no upper limit)
Total NPV (million SEK)	39960	37806
NPV for harvest (million SEK)	42052	41949
PV for transportation (million SEK)	5255	7158
NPV for forest biofuel extraction (million SEK)	3163	3015
Average harvest level (million m^3 per year)	5.48	5.42
Average carbon sequestration (million tonnes per year)	1.47	1.48

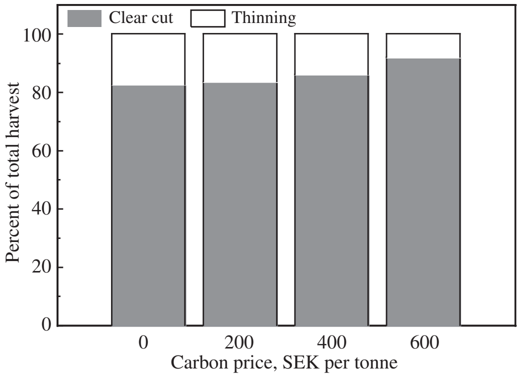

Fig. 9. Proportion of thinning and clear-cut volumes relative to the total harvested volume. Values are average for a 100-year period.

was partly compensated by increased clear-cut levels in the eastern parts.

3.3 Effect of an Upper Limit on Transportation Prices

So far the results are based on the true, unconstrained transportation cost, i.e., with no upper limit (Eq. 2). Under the assumption of an upper limit for the transportation cost and carbon price set at zero, total NPV increased by the combined effect of reduced transportation costs and increased harvest levels, almost 6% for the whole county (Table 1). As a result of increased harvesting, carbon sequestration decreased. When the scenario with the true transportation cost was applied, harvesting decreased in the western parts and increased in the eastern parts (Fig. 10), thus accentuating the east–west gradient of harvest intensity.

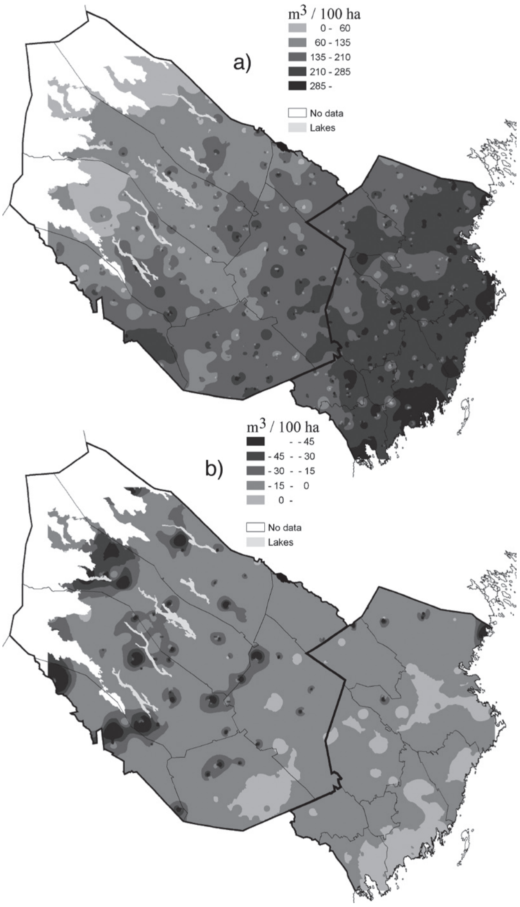

Fig. 10. Average harvest level (m^3 per 100 hectares per year) using the current transportation cost, with an upper limit map a). Map b) shows the change in average harvest level (m^3 per 100 hectares per year) when full transportation cost was applied. The average value is the mean for all forest land including the unharvested area.

4 Discussion

4.1 Regional Outcomes

Within the region considered there are obvious variations concerning timber and forest biofuel production potentials as well as the potential for using forests for mitigating CO_2 emissions. The difference in harvest levels between the western and eastern part of Västerbotten, given any carbon price, is due to the differences in transportation costs and site productivity. Since the production per unit area is lower in the western part, there is a relatively smaller trade-off with carbon sequestration. This result is in line with Huston and Marland (2003), who suggest that relatively unproductive forests could be used for both carbon uptake and preserving biodiversity. The level of carbon sequestration was governed by the harvest level and the site productivity. We showed that decreasing the harvest activities led to increased carbon sequestration, especially in areas with high productivity. One would expect that a considerable reduction of the harvest level in the western parts of the county would have a negative influence on the local economy and job opportunities within forestry. However, due to the mechanization of harvest operations, concentration of industries to the coast and the Swedish tax system, forestry is not of major importance to the local economy (Lindgren et al. 2000). A reduction of the harvest levels in the western parts of the region would therefore probably affect job opportunities within forest industries in the eastern as much or even more than in the western areas.

The standing wood volume in the region increased with increased carbon price, mainly through decreased harvest. In this case, the thinnings were excluded from the solution before the clear-cuts. This is logical as the net profit from thinnings is lower than the net profit from clear-cuts. As the carbon price increased, the net profit for carbon storage approaches the same value as the net profit from thinnings. Also, the harvest of wood was imposed with a carbon cost ($PV^{C\text{-emission}}$) that was discounted in the same way as all the other incomes and costs. However, this cost is larger if the harvested wood goes mainly to the pulp industry as the carbon in the wood is released faster in pulp and paper products compared to sawn wood. Thus the discounting effect makes the cost of carbon emissions larger for pulpwood than for timber.

4.2 Carbon Storage

The mean annual carbon storage increase for the whole county and the 100-year period predicted in our scenario with a zero carbon price was 0.46 tonne per hectare. This is higher than the present level reported in Sweden's National Inventory Report 2004 to the United Nations Framework Convention on Climate Change (Feldhusen et al. 2004). The report claims an annual carbon increase on forest land in Sweden in the period 1990–2002 of 0.25 tonne per hectare.

Although carbon sequestration in forest might not be a permanent carbon sink, there are several benefits. First of all it is a possibility for buying time. This time gain may delay temperature increase, and thus potential damages. Also time can be used for converting fossil fuel to biofuel, for technological progress, capital turnover for investments in fossil fuel technology, and allowing for learning to take place (Marland et al. 2001). Sequestration in forest is flexible and actions are often reversible, which is an advantage in an uncertain future (Solberg 1997, Van Kooten at al. 1997). Moreover, the cost of carbon uptake is often well known (Van Kooten et al. 1997) compared to cost for potential future damages caused by climate change.

Another concern related to carbon sequestration in the forest is how much carbon forests can carry, also called the saturation issue. Considering the shape of the curve in Figure 3, it seems that 100 years were not enough for reaching some kind of a steady state in standing volume. The conclusion is, that there is no risk of carbon saturation over the next 100 years for the forest studied in this region, given that the net growth according to the growth model reflects carbon sequestration. There is, however always a risk that large scale disturbances such as wildfire, pests, etc., may turn the forest into a temporary carbon source.

4.3 Forest Biofuel

Introducing a carbon price as described in this study led to lower harvest levels and less areas, where forest biofuel was extracted. However, at low carbon prices there was a small increase in the amount of biofuel harvested, because the reallocation of final harvest to economical efficient treatment units means that biomass harvests were larger. So, in short, this is an effect of the concentration of harvest activities towards the coast.

The results show that atmospheric carbon mitigation through carbon sequestration in forest biomass has a higher mitigation potential than fossil fuel substitution by forest biofuel. The amount of carbon mitigation originating from the use of forest biofuel instead of fossil fuel was around 19 kg per hectare per year (for carbon prices between zero and 300 SEK per tonne). This is lower than that reported in a study in the county of Dalarna in the middle of Sweden. Ericsson (2003) reported that the potential carbon mitigation through the use of forest biofuel was around 50–100 kg per hectare per year in Dalarna. The difference between the study in Dalarna and our study is that we optimized the NPV of several utilities, while Ericsson did simulations with the Hugin system (Lundström and Söderberg 1996) aimed at attaining the highest sustainable harvest level and simulated (in the base scenario) harvests of biofuel at 10% of the clear-cut area. Also, the productivity in Dalarna is 3.8 m^3 per hectare per year, while the productivity in Västerbotten is 2.8 m^3 per hectare per year (Skogsdata 2004). It is also worth noting that our conversion factor and that used by Ericsson (2003) is only replacing oil and no other fossil fuel and may therefore not be fully representative. We can conclude that, with today's prices and our assumptions, it is not possible to achieve higher harvest levels of forest biofuel. However, our assumptions are quite narrow so the amount of forest biofuel harvested could probably be increased considerably if biofuel harvest is allowed in thinnings and if fertilization was applied at suitable sites. As mentioned in the introduction, estimates of the biomass potential in Sweden show that optimized fertilization and the use of excess stem wood could almost double the biofuel potential (Börjesson et al. 1997). Although the amount of harvested forest biofuel is small, it has the advantage of being permanent, as it is CO_2-neutral and replaces fossil carbon. The carbon stored in forest biomass can, in time, be released back into the atmosphere through natural mortality or the use of forest products. If only a part of the carbon stored in forest biomass would be accounted for, like in the Kyoto Protocol, the production of biofuel would be more competitive for mitigating climate change. Such a policy would probably also accentuate the east-west gradient found in this study.

Harvesting of forest biofuel can affect the nutrient status of the forest soil. The magnitude of this effect is not absolutely clear, but Egnell et al. (1998) have suggested that the needles are left at the harvesting site and that nutrient loss is compensated for by fertilization. Also, the carbon stock in the soil can be affected by removing the tops, branches and needles. However, Ågren and Hyvönen (2003) modeled the change in soil carbon stock and found that removing the needles has only a small effect on the soil carbon stock because the needles removed by harvesting represent only a small amount of the total needle production during a rotation. We did not include the soil in the calculations, and this naturally led to a limited picture of the problem, as the carbon pool in soils is more than five times larger than in biomass in the boreal forest (IPCC 2000). Including the soil would demand an interaction between the linear programming model, the forest model and a soil model. Due to the lack of a soil model that easily could be incorporated in the model, soil factors were excluded from the study. Simulations studies (without interaction with any optimizing program) for both stand and regional scale analysis of biomass and soil carbon are however performed with models like CO2FIX (Nabuurs et al. 2002, Masera et al. 2003), MOTTI (Hynynen et al. 2005) and EFISCEN (Karjalainen et al. 2002). All these three models are linked to a dynamic soil carbon model called Yasso (Liski et al. 2005). Results from this model, linked to different biomass models, shows a soil carbon sink in Norway and Finland varying from 0.08 tonne C per hectare and year (de Witt et al. 2006) up to 0.17 tonne C per hectare and year (Liski et al. 2005). In Sweden, using the Q-model (Rolff and Ågren 1999) and reference scenarios, Ågren and Hyvönen (2003) and Ericsson (2003) estimated the soil carbon sink to 0.17 and 0.25 tonne C per hectare and year, respectively. For comparison, the carbon soil pool is estimated to about 74 tonne C per hectare on productive forest land in Sweden (Lilliesköld and Nilsson 1997). Inclusion of the soil carbon in our problem, would strengthen the carbon sequestration value of the forest, if soil carbon storage increases for low harvest levels.

4.4 Factors not Included

Not all the components of carbon sequestration related to forests and forestry were included, and in the model used, some components were more uncertain than others.

Carbon in soils (see discussion above), emissions from transportation of wood and wood products, and emissions from wood harvested before the start of the planning horizon, were not included in the model. Furthermore, our data set lacked information on the amount of dead wood for the initial period. The change in biomass (living and dead) between periods 1 and 2 is therefore overestimated, because the change in dead wood increases from zero to the amount formed in period 2. Instead of starting from zero, one could have simulated dead wood on the plots. This would, however, be an uncertain procedure as there is a large local variation in the amount of dead wood in the studied area. Fridman and Walheim (2000) found the amount of dead wood in the studied area to be between 5.6 and 9.7 m^3 per hectare while Lämås and Fries (1994) estimated that the amount of dead wood was 1.74 m^3 per hectare in a large forest area (8600 hectare) in Västerbotten. Our projection of dead wood biomass is intricate to compare to monitored values. Typically, studies of dead wood biomass, including the two studies mentioned, only consider dead wood above ground and do not include the stumps and roots. The density for dead wood in the decomposition process is lower than the density in living biomass and therefore making comparison between volume and weight imprecise. We have used decomposition functions for above ground parts presented by Harmon et al. (2000). Although they are for above ground parts, we used them also for below ground parts, as no other suitable functions exits. The growth and mortality models used are based on data mainly from managed forest (NFI data) causing predictions for unmanaged forests and low-intensity forest management to be more uncertain than those made under management according to conventional prescriptions. Thus, the amount of carbon sequestrated using high carbon prices, i.e., low cutting levels, may be more uncertain than the amounts estimated for lower carbon prices. Furthermore, our method to search for optimal management programs might result in better management than actually is performed in practical forestry. Another cause of potential discrepancy is that we have not considered possible effects of biofuel extraction, on long term site productivity.

4.5 Economic Factors

In the study, timber, pulpwood, and biofuel prices were held constant. In reality, the introduction of a carbon price would affect these prices. Such a dynamic was not part of the study. In this case a separate region was studied, but if a carbon credit was applied for only one separate country (or region), that country's forest industry would be priced out quite soon as wood and pulp markets are global. Policies for carbon sequestration in forest should therefore not be applied for a single country or region alone.

The comparison between the two different transportation costs shows, as expected, that if the forest owners must pay the full transportation cost, harvest volumes and NPVs will decrease. This is especially apparent for the municipalities in the western part of the county. The reason for this was the very long transportation distance to the pulp mill at the coast. Although the full transport cost policy made the differences within the region larger than the cost policy presently applied in the region, it is an appropriate approach on a regional perspective, as transportation always has to be paid for by someone.

4.6 Conclusions

This study shows that detailed analysis on a regional scale is possible using NFI data and mathematical models. It also underlines the necessity to examine the consequences of different approaches to increase the forests' ability to mitigate the increase of CO_2 in the atmosphere. The kind of model presented here can be of help when evaluating different policies related to carbon sequestration issues, for example by revealing unexpected effects. We found that introducing a carbon price reduced harvest levels, and the effect was more pronounced on low production areas far away from the industry. The thinning proportion of total harvest volume decreased, as carbon prices increased. Our assumptions resulted in less carbon mitigation potential for forest biofuel than storing carbon in forest.

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Appendix

The maps were created by laying a grid over the area. At each intersection a weighted average was calculated for all plots within a radius of 25 km from the intersection. The area weights for the plots were calculated as:

$$w = (x - y)^2$$

where w = area weight, x = radius for the calculated area (25 km) and y = plot distance from the center of the calculated area. This method accentuates local variation.