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Optimal Forest Management with Carbon Benefits Included

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In this paper, we analyse how optimal forest management of even aged Norway spruce changes when economic values are placed on carbon fixation, release, and saved greenhouse gas emissions from using wood instead of more energy intensive materials or fossil fuels. The analyses are done for three different site qualities in Norway, assuming present climate and with a range of CO_2 prices and real rates of return. Compared to current recommended management, the optimal number of plants per ha and harvest age are considerably higher when carbon benefits are included, and increase with increasing price on CO_2. Furthermore, planting becomes more favourable compared to natural regeneration. At the medium site quality, assuming 2% p.a. real rate of return and € 20 per ton CO_2, optimal planting density increases from 1500 per ha to 3000 per ha. Optimal harvest age increases from 90 to 140 years. Including saved greenhouse gas emissions when wood is used instead of more energy intensive materials or fossil fuels, i.e. substitution effects, does not affect optimal planting density much, but implies harvesting up to 20 years earlier. The value of the forest area increases with increasing price on CO_2, and most of the income is from carbon. By using the current recommended management in calculations of carbon benefit, our results indicate that the forest's potential to provide this environmental good is underestimated. The study includes many uncertain factors. Highest uncertainty is related to the accuracy of the forest growth and mortality functions at high stand ages and densities, and that albedo effects and future climate changes are not considered. As such, the results should be viewed as exploratory and not normative.

Keywords CO_2, greenhouse gas mitigation, forest management, optimisation,
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1 Introduction

Human induced accumulation of greenhouse gases in the atmosphere is now seen as the main cause of global warming (IPCC 2007a, b), and reducing greenhouse gas emissions from use of fossil fuels and deforestation is high on the political agenda. Carbon sequestration in forests has been discussed as a mitigation option for a long time, mainly because it is a cost-effective option compared to reducing use of fossil fuels (e.g. Richards and Stokes 2004). Carbon fixation and release from land use change and forest activities is included in the Kyoto Protocol, and is also discussed in several reports from The Intergovernmental Panel on Climate Change (IPCC 2001, 2007b). The forests as providers of a renewable resource that can be used instead of energy intensive materials and fossil fuels has also been recognised (IPCC 2007b).

Deforestation accounted for about 20% of the worlds CO_2 emissions in the 1990s (IPCC 2007b) and is consequently the forest activity given most attention on a worldwide basis. In developed countries, however, enhancing the carbon benefit on existing forested land or afforestation are the most discussed issues. Future carbon fixation and release from forests is dependent on climatic conditions, but also to a large degree on how we manage them. In previous literature (e.g. Chen et al. 2000, Liski et al. 2001, Schlamadinger and Marland 1996) the forest management is generally viewed as something static, where harvest age and other key management options are held constant. In reality, we can optimise the carbon benefit from forests by adjusting harvest and regeneration.

The aim of this article is to study, at stand level and present climate, which forest management is optimal with various real rates of returns and prices of CO_2, and how the optimal forest management will change if saved greenhouse gas emissions from using wood instead of more energy intensive materials or fossil fuels (substitution effects) are included. We define optimal as the forest management that maximises total revenue, i.e. net present value of timber revenue plus net present value of revenue from CO_2 benefit. The research questions are: 1) Should we plant or wait for natural regeneration, and if we plant, how many plants should we invest in per ha? 2) When should we harvest in order to maximise the total revenue from the forest? 3) When, if at all, should we carry out release thinning or thinning? 4) How do the answers to these questions change when substitution effects are included? The analyses are done for Norway spruce at three common site qualities in Norway (low, medium, and high). Results are demonstrated for six different prices on CO_2 (€ 0, 5, 10, 15, 20, and 41 per ton), and four different real rates of returns (2, 3, 4, and 5% p.a.).

Several studies have compared the carbon benefit from managed versus unmanaged forests. Karjalainen (1996a) and Seely et al. (2002) found that carbon storage is higher in unmanaged stands than in managed ones, in analyses for Finland and British Columbia, respectively. Schlamadinger and Marland (1996) compared various management strategies for a forest site in Western Europe/Southeastern US and found that leaving the forest unmanaged can have the highest carbon benefit, but that this depends on how efficiently wood is used to substitute other materials. Price et al. (1997) found that no management gave lower carbon storage than management that involved constant harvest and suppression of fires and insect attacks in Alberta, Canada. The reason for this was that the rotation length on average was longer than the interval between natural disturbances.

Other studies have found that longer rotation lengths give higher carbon storage (Lunnan et al. 1991, Liski et al. 2001, Seely et al. 2002, Ericsson 2003). This is not surprising since a longer rotation results in more years of carbon fixation. In fact, Backéus et al. (2005) did a study where harvest age was endogenously determined in the model and found that there would not be any harvest in Västerbotten in Sweden if there was a carbon price of € 30 per ton CO_2. Karjalainen (1996b) studied how thinning regimes influenced carbon storage in mixed species stands in Finland, and found that thinning from above was most favourable for carbon fixation, in some cases better than no management. Pohjola and Valsta (2007) found optimal thinning programmes and rotation ages for Scots pine and Norway spruce stands in Finland, for three different prices of

CO_2. Their results showed that positive carbon prices lead to longer rotations, and later, to some extent lighter, thinnings.

For Buskerud County in Norway, Hoen and Solberg (1994, 1999) found that more planting and less natural regeneration was optimal when more weight was given to carbon benefit. This is because of the gain in years of carbon fixation instead of waiting for natural regeneration. Similar results were found by Raymer et al. (2009) for Hedmark County, Norway.

No studies have to our knowledge looked at optimal planting density with a value on carbon fixation, and seen it in connection with other silvicultural alternatives and harvest timing. In traditional forestry, more is invested in regeneration on forest sites with good growing conditions than on sites with lower productivity. That is, planting instead of natural regeneration and more plants per ha. The analysis in this paper shows that, with a value on carbon, planting will be more attractive compared to natural regeneration on all sites. A value on CO_2 also makes it optimal with higher planting densities than what is currently recommended.

Another aspect previously unexplored is how optimal forest management changes when saved greenhouse gas emissions from the use of wood products are taken into account, although several studies have included substitution effects in their analyses (Schlamadinger and Marland 1996, Shvidenko et al. 1997, Chen et al. 2000, Ericsson 2003). Raymer et al. (2009) included substitution effects in their analysis of optimal forest management, but found few differences with and without including substitution because the harvest level was held fixed at the present level to avoid issues with timber supply, forest owner activity, and leakage effects. Our analysis show that a high value on carbon will make it optimal to postpone harvest in order to achieve more years of fixation and postpone release after harvest, when income/costs from carbon benefit is weighted according to when in time they occur, i.e., discounted. Including substitution effects would favour a somewhat lower harvest age in order to bring the substitution effects closer in time, but have little effect on planting density.

To what degree optimal harvest age and investments in regeneration will change depends on the value of timber versus the value of carbon benefit, and on the real rate of return. The real rate of return is a very important factor when determining economic optimal management practices, as investments in regeneration, thinnings, and prolonged rotations decreases rather quickly with increasing real rates of return.

2 Methodology and Assumptions

2.1 Forest Area

The three site qualities studied represent G11, G14, and G17 in the Norwegian site index system (H_{40}). Here, the letter G refers to Norway spruce and the numbers 11, 14, and 17 to dominant height in metres when the stand is 40 years (age measured 1.3 m from the ground) (Tveite 1977). The three chosen site qualities represent a low, medium, and good site according to Norwegian conditions. In Southern Norway (altitude < 300 m), G11 reflects the *Myrtillus* vegetation type, G14 the *Oxali* vegetation type, and G17 the *Aconitum* vegetation type (Børset 1985b). The forest area is bare at the beginning of the planning period and all figures are for one ha.

2.2 Model

The analysis is based on applying the stand growth simulation model GAYA. The model, particularly the carbon accounting part, is described in detail in Raymer et al. (2009). GAYA projects possible developments for each forest stand on a 5 year basis based on empirical functions for growth, natural mortality, and seven stand treatments: no intervention, release thinning in young growth, thinning, fertilisation, clear felling, clear felling with retention of seed trees, and planting or natural regeneration. Based on feasibility requirements set exogenously for each treatment, all possible management programmes within the feasibility limits are simulated for each stand over the specified planning horizon. The feasibility requirements used in our analysis are specified in Table 1, and cover all realistic forest management

Table 1. A priori feasibility requirements for forest management in the simulations.

Forest management alternatives	Feasibility restrictions
No interventions	–
Release thinning in young growth	Number of stems per ha minimum 2500, dominant height 2–8 meters, can be performed maximum 2 times
Thinning	Number of stems per ha minimum 1200, dominant height 12–18 meters, basal area minimum 15 m^2 per ha, can be performed maximum 2 times
Clear felling	Age of stand 60–160 years, with intervals of 5 years
Natural regeneration	1500 trees per ha after 20 years
Planting	800–4000 plants per ha with an interval of 100 plants per ha. The planting density used in year 0 is fixed for subsequent rotations. No supplementary planting.

options in Norway except fertilisation. In practice, we restricted the number of alternatives to a finite set of planting densities and simulated all management schedules for these discrete alternatives. We identified the management schedules with highest net present value using J (Lappi 2005), although any software capable of sorting a large amount of data could have been used.

Compared to previous studies using GAYA, several planting densities have been simulated. Number of plants per ha can in this analysis vary from 800–4000 plants per ha with an interval of 100 plants per ha. The upper limit of 4000 plants per ha was chosen in order to keep within a reasonable accuracy of the growth and mortality functions. The only final harvesting method is in our analysis clear felling. Another difference from previous studies using GAYA is that we have applied the mortality functions developed by Eid and Øyen (2003), where mortality is a function of stand density.

The focus of our analysis is flows, or fluxes, of CO_2, defined as net exchange of CO_2 between the extended forest ecosystem and the atmosphere from one period to the next. The model takes the time perspective of CO_2 flows into account by discounting the value of net CO_2 removal to a present value. This approach is called levelization, or discounting, in the overview of cost-effectiveness of carbon sequestration of forest projects in Richards and Stokes (2004). Because we study removal of CO_2 from the atmosphere (and emission of CO_2 to the atmosphere), the unit in GAYA is 1 ton CO_2, but amount of carbon can be calculated by multiplying with the conversion factor 12/44.

Finding flows of CO_2 and stocks of carbon is on one hand two ways of studying the same thing, as flows are changes in the stocks over time. Methodologically, the approaches are, however, quite different. Calculating flows of CO_2 is necessary in order to take the time perspective into account, and is the approach used in studies using optimization models (Hoen and Solberg 1994, Backeus et al. 2005, 2006, Pohjola and Valsta 2007) where carbon directly or indirectly is given a value and it matters when in time emissions or removals from the atmosphere happens. In our study we focus on greenhouse gas implications of choices we can make with regard to present and future forest management, and view greenhouse gas emissions from previous forest management as sunk costs. Since the emission rates in our model are linear with respect to the carbon stock quantity, we find net exchange of CO_2 between the forest and the atmosphere without information on the initial stocks of carbon in dead wood, soil or wood products. The emission rates are based on empirical data, references are given below in the description of the model.

In the model, three processes influence the net exchange of CO_2 between the atmosphere and the forest; (1) fixation in growing biomass, (2) release from decaying biomass, soil, and wood products, and (3) saved greenhouse gas emissions when wood is used instead of fossil fuels or energy intensive materials (substitution effects).

Volume growth and carbon fixation in growing trees are in GAYA calculated using Norwegian growth and yield functions and the biomass functions in Marklund (1988). Natural mortality is, as mentioned above, modelled using the functions in Eid and Øyen (2003). For Norway spruce, which is the focus in this analysis, the trees are assumed to loose 14% of their needles per year (Børset 1985a). The same quantity of needles that is lost is produced, i.e. the needles are renewed and CO_2 fixated. Similarly, spruce trees loose 2% of their branches per year (Ågren and Hyvönen 2003). Fine root annual turnover is 64.1% (Li et al. 2003).

Decomposition of dead wood from natural mortality, litter, and harvest residues is modelled with the YASSO model (Liski et al. 2005). This is a process based model that calculates flow of carbon from dead biomass and soil to the atmosphere. In YASSO, there are four different categories of dead biomass (non-woody litter, fine woody litter, coarse woody litter with diameter < 20 cm, and coarse woody litter with diameter > 20 cm), and five different soil compartments (soluble compounds, holocellulose, lignin, fast decaying humus, and slow decaying humus), with decomposition and fractionation rates ranging from fast to slow.

Release of CO_2 from wood products is modelled with the same assortments and corresponding decay times as in Hoen and Solberg (1994), based on anthropogenic lifetime, i.e. how many years the product is used, and its subsequent decay time. The latter is defined as number of years until 90% of the product has decayed. Basically, the products are used and the carbon in them stored for a certain period. Then the products gradually go out of use because of demolition or replacement, and the carbon is released to the atmosphere following an exponential function.

Saved greenhouse gas emissions, or substitution effects, are in the model included in two ways: one is saved greenhouse gas emissions when wood products are produced instead of other materials, the other is saved greenhouse gas emissions when bark, fuel wood, and demolished wood products are used as energy instead of fossil fuels (Raymer et al. 2009). The parameters in the model are based on saved greenhouse gas emissions (CO_2, CH_4, and N_2O) per m^3 wood used as energy or for a mix of wood products reflecting how harvested timber is used in Norway as described in Raymer et al. (2009). Saved greenhouse gas emissions are defined as net greenhouse gas savings; greenhouse gas emissions from competing products minus greenhouse gas emissions from wood products.

2.3 Optimisation and Economic Data

The optimisation problem is to maximise the net present value of the forest site, including both timber and carbon revenue. The decision variables are the forest management alternatives defined in Table 1. The planning horizon is 150 years, or 30 5-year periods, but the model follows the decay process of dead wood, harvest residues, and wood products for 625 years to include all CO_2 emissions. At the end of the simulation period, the value of the standing forest and the soil expectation value are calculated using the current recommended forest management, to avoid inconsistent measures in the last period of the planning horizon.

The optimization problem can be described formally as

$$\text{Max Total NPV} = \sum_{p=1}^{P}\left(\text{NPV}_{\text{timber}} + \text{NPV}_{\text{CO}_2}\right)$$

$$= \sum_{p=1}^{P}\left(\frac{H_p - L_p - C_p + \left(F_p - R_p + S_p\right)z}{(1+r)^{p\times l}}\right)$$

where

$p =$ Period

$P =$ Planning horizon, or simulation period (150 years or 30 periods)

$l =$ Period length (5 years)

$r =$ Real rate of return (2, 3, 4, and 5% p.a.)

$H_p =$ Income from sale of timber in period p

$L_p =$ Logging cost in period p

$C_p =$ Planting cost in period p

$F_p =$ Fixation of CO_2 in period p

$R_p =$ Release of CO_2 from an event in period p followed 125 periods into the future, discounted back to period p

$S_p =$ Substitution effects from an event in period p followed 125 periods into the future, discounted back to period p

$z =$ Value of 1 ton CO_2 (€ 0, 5, 10, 15, 20, and 41)

The analyses are done with real rates of returns of 2, 3, 4, and 5% p.a., reflecting a realistic range of real rates of returns for Norwegian forest owners. Prices and costs are assumed to be constant throughout the planning horizon.

The price of one spruce plant is on average € 0.25 from the largest suppliers in Norway. The labour cost is on average € 0.31 per plant. Harvesting cost, cost of thinnings, and release thinnings are from Hoen et al. (1998) and are dependent on both volume per tree cut and number of trees extracted per ha, thus giving higher costs for extracting small trees and volumes compared to larger ones. In 2005 the price of saw logs from spruce timber was on average € 52.5 per m^3, the price of pulpwood from spruce timber € 28.75 per m^3. The prices for various tree sizes (delivered roadside) is based on the price functions in Blingsmo and Veidahl (1992), which give higher value per m^3 for larger trees, reflecting the price differences between sawn wood and pulpwood in the Norwegian timber market, and the price premiums according to size for the saw logs.

We have chosen six levels for the price of CO_2: € 0, € 5, € 10, € 15, € 20, and € 41 per ton CO_2. € 0 per ton CO_2 reflects the present situation where there is no market for CO_2 credits in forests. € 5, € 10, € 15, and € 20 shows a realistic range of the CO_2-price in the European market for carbon trading, and the long term marginal damage cost (Fankhauser 1994, Tol 2005). € 41 per ton CO_2 is similar to the present CO_2-tax on petrol in Norway.

3 Results

Fig. 1 shows the relationship between planting density and net present value of the forest sites for real rate of return 2% p.a. Number of plants per ha is shown on the horizontal axis, net present value on the vertical axis. The upper two graphs show the results for site quality G17, the middle site quality G14, and the two bottom ones site quality G11. The graphs to the left show the results without including saved greenhouse gas emissions from use of wood products and wood energy, the graphs to the right shows the results including this effect.

Using site quality G14, excluding substitution effects, in Fig.1. as an example; we see that the net present value increases substantially the higher the price on carbon. Maximum net present value is twice as high with a CO_2 price of € 5 and 10 times as high with a CO_2 price of € 41. Net present value is determined by two factors: planting density and harvest age. In Fig. 1, net present value is shown for the management programme that gives the highest net present value for each planting density. Table 2 gives net present value, planting density, and harvest age for the planting density with highest net present value. The table also shows how much of total net present value is from timber and CO_2 respectively (we have for simplicity allocated all planting costs to timber revenue). The higher the CO_2 price, the higher the income from CO_2. In fact, at site quality G14 the net present value from timber revenue is negative with a CO_2 price of € 41.

At site quality G14, the optimal planting density starts out at 1500 per ha with a CO_2 price of € 0 (see Table 2), and increases to 4000 per ha with a CO_2 price of € 41 (the latter is the value at limit, and the real optimum could be higher). The optimal harvest age increases with increasing price of CO_2, from 90 to 140 years. Postponing harvest has two positive effects on carbon benefit: (1) More years with CO_2 fixation and (2) postponement of CO_2 emissions from decaying harvest residues and short lived wood products following harvest. These two positive effects are higher than the loss of carbon fixation in new forest established after felling. There is a substantial build up in standing volume with a price on CO_2. With no value on CO_2 the standing volume is 595 m^3 per ha when the stand is harvested, while this figure is 1244 m^3 per ha with a CO_2 price of € 41 per ton.

Current recommended management for site quality G14 is similar to the alternative with no value on CO_2. Without a value on CO_2 it is optimal to plant 1500 plants per ha and harvest after 90 years. Using this management when there is a value on CO_2 gives an underestimation of carbon benefit from 14–72% discounted ton CO_2-equivalents per ha compared to using optimal planting density and harvest age. So even though the curves in Fig.1 appear flat, i.e. no large difference in net present value around optimal planting densities with corresponding management programmes, using fixed management schedules based on current recommended management (price CO_2 € 0) may lead to a sub-

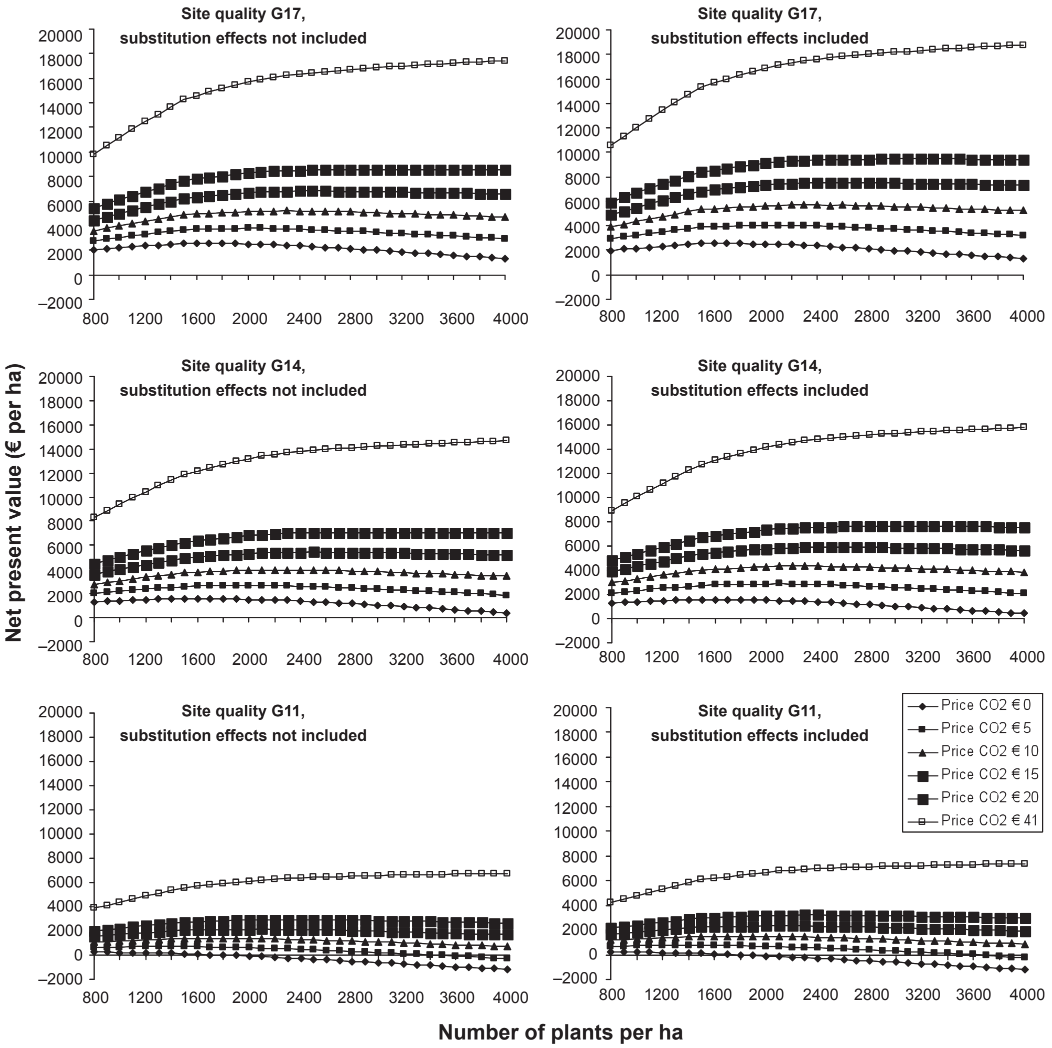

Fig. 1. Net present value as a function of planting density with 2% p.a. real rate of return, for site qualities G11, G14, and G17, with and without substitution effects, and six different CO_2 prices.

stantial underestimation of the forests potential for providing carbon benefits.

Comparing the results excluding and including substitution effects, net present value of the site is the same with a CO_2 price of € 0. With a value on CO_2, net present value is 7–9% higher when substitution effects are included at site quality G14 and 2% p.a. real rate of return. The reason for the difference not being larger is that the value of CO_2 is discounted, and saved greenhouse gas emissions from use of wood products and energy come after harvest, which is more than 100 years into the future. Optimal planting density is similar with and without substitution effects for site quality G14 (see Table 2). Harvest age is, however, 5–10 years lower when substitution effects are included for CO_2 prices of € 15–41. If substitution effects are included there is an additional income from saved greenhouse gas emissions from use of wood products after harvest. This makes it favourable to harvest somewhat sooner than when substitution effects are not included.

Table 2. Net present value, planting density, and harvest age for the optimum of the curves in Fig. 1. with 2% p.a. real rate of return.

		Price CO_2 (€ per ton)					
		0	5	10	15	20	41
Site quality G17 without substitution							
NPV (€ per ha)	Total	2558	3774	5206	6813	8595	17446
	Timber	2558	2426	2063	1832	814	55
	CO_2	0	1348	3142	4982	7782	17388
Plants per ha		1500	2100	2300	2500	3200	4000
Harvest age (years)		80	90	105	110	130	140
Site quality G17 with substitution							
NPV (€ per ha)	Total	2558	4041	5700	7521	9461	18785
	Timber	2558	2426	2272	1920	1506	210
	CO_2	0	1615	3428	5601	7956	18573
Plants per ha		1500	2100	2300	2600	3100	4000
Harvest age (years)		80	90	95	105	110	135
Site quality G14 without substitution							
NPV (€ per ha)	Total	1583	2677	3976	5441	7073	14662
	Timber	1583	1462	1295	751	265	–284
	CO_2	0	1215	2681	4691	6808	14945
Plants per ha		1500	2100	2200	2500	3000	4000
Harvest age (years)		90	100	110	130	140	140
Site quality G14 with substitution							
NPV (€ per ha)	Total	1583	2868	4333	5895	7631	15786
	Timber	1583	1462	1295	963	381	–284
	CO_2	0	1407	3038	4932	7250	16072
Plants per ha		1500	2100	2200	2500	3000	4000
Harvest age (years)		90	100	110	120	135	135
Site quality G11 without substitution							
NPV (€ per ha)	Total	247[1]	728[1]	1385	2138	2937	6759
	Timber	247	88	31	–220	–316	–1244
	CO_2	0	640	1354	2358	3252	8003
Plants per ha		800	1500	1500	2100	2300	4000
Harvest age (years)		80	90	100	110	130	140
Site quality G11 with substitution							
NPV (€ per ha)	Total	247[1]	794[1]	1506	2339	3212	7376
	Timber	247	108	62	–220	–316	–1244
	CO_2	0	687	1444	2559	3528	8618
Plants per ha		800	1500	1500	2100	2300	4000
Harvest age (years)		80	90	95	105	110	140

[1] Natural regeneration gives a higher net present value than planting

At the best site quality G17, the net present values are higher because of better growing conditions and higher yields. Optimal planting density increases with increasing CO_2 price, from 1500 to 4000 per ha (Table 2), and is in the same order of magnitude as for G14. Harvest age is lower than at site quality G14 because of faster growth, except with the highest price of CO_2.

There are some differences in optimal planting density with and without including substitution effects at site quality G17. With CO_2 price € 15 optimal planting density is 100 plants per ha higher when substitution effects are included, with CO_2 price € 20 100 plants per ha lower. The higher volume per ha, the higher the substitution effect. At first sight this would imply larger

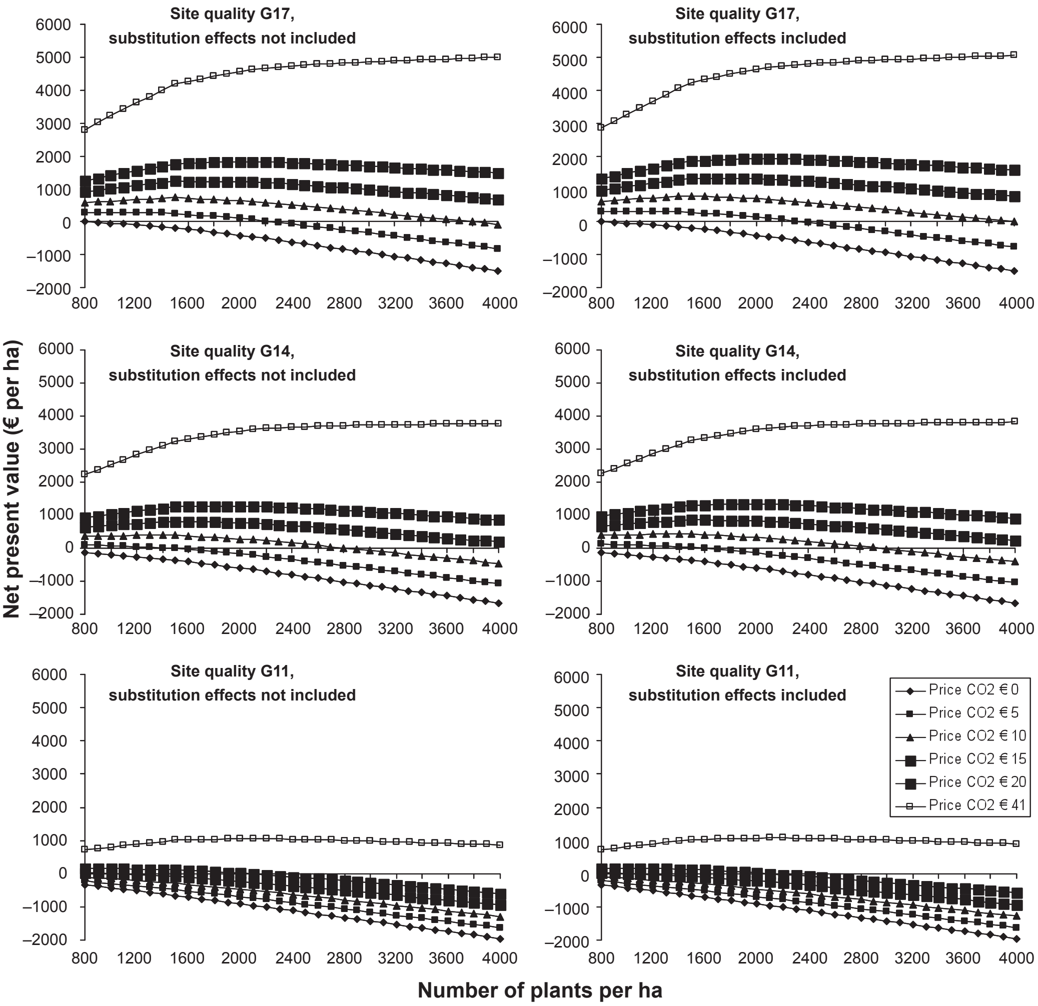

Fig. 2. Net present value as a function of planting density with 4% p.a. real rate of return, for site qualities G11, G14, and G17, with and without substitution effects, and six different CO_2 prices.

number of plants per ha. However, there are two main decision variables in the model; number of plants per ha and harvest age. The difference in harvest age between excluding and including substitution effects is 5–20 years for CO_2 prices € 10–41. So, including substitution effects has a larger effect on optimal harvest age than on optimal planting density, and number of plants per ha can be both higher and lower. Overall, including substitution effects do not influence number of plants much. There is only one other example, site quality G17 with a CO_2-price of € 20 and a real rate of return of 3% p.a. (see appendix).

At the lowest site quality G11, the net present values are lower because of lower yield. The main difference compared to G14 and G17 is that natural regeneration gives a higher net present value than planting for CO_2 prices € 0 and 5, even though planting is profitable. Optimal planting density is lower than at the better site qualities except with the highest CO_2 price, where it reaches the highest planting density included in our study, similar to the other site qualities. Optimal harvest age is lower at site quality G11 than at G14. This seems to be in contrast to common knowledge showing that economic optimal harvest age is higher the

Table 3. Maximum net present value and the corresponding planting density and harvest age with 4% p.a. real rate of return.

		Price CO_2 (€ per ton)					
		0	5	10	15	20	41
Site quality G17 without substitution							
NPV (€ per ha)	Total	3[1]	282[1]	729	1231	1824	4997
	Timber	3	–5	–255	–341	–706	–1925
	CO_2	0	287	984	1572	2530	6921
Plants per ha		800	800	1500	1500	2100	4000
Harvest age (years)		65	70	80	90	100	140
Site quality G17 with substitution							
NPV (€ per ha)	Total	3[1]	306[1]	789	1312	1920	5057
	Timber	3	–31	–255	–297	–613	–1882
	CO_2	0	337	1045	1610	2534	6937
Plants per ha		800	900	1500	1500	2100	4000
Harvest age (years)		65	70	80	85	90	130
Site quality G14 without substitution							
NPV (€ per ha)	Total	–126[1]	109[1]	389[1]	811	1279	3770
	Timber	–126	–139	–440	–498	–789	–1939
	CO_2	0	249	829	1310	2068	5707
Plants per ha		800	800	1500	1500	2000	4000
Harvest age (years)		70	80	90	100	110	140
Site quality G14 with substitution							
NPV (€ per ha)	Total	–126[1]	125[1]	431[1]	862	1336	3819
	Timber	–126	–139	–414	–440	–728	–1939
	CO_2	0	265	845	1302	2064	5756
Plants per ha		800	800	1500	1500	2000	4000
Harvest age (years)		70	80	85	90	100	140
Site quality G11 without substitution							
NPV (€ per ha)	Total	–333[1]	–223[1]	–104[1]	23[1]	155[1]	1049
	Timber	–333	–337	–350	–370	–375	–1022
	CO_2	0	114	247	393	530	2071
Plants per ha		800	800	800	800	800	2100
Harvest age (years)		90	100	115	135	140	140
Site quality G11 with substitution							
NPV (€ per ha)	Total	–333[1]	–218[1]	–97[1]	31[1]	162[1]	1073
	Timber	–333	–337	–346	–356	–370	–1022
	CO_2	0	119	249	387	532	2095
Plants per ha		800	800	800	800	800	2100
Harvest age (years)		90	100	110	120	135	120

[1] Natural regeneration gives a higher net present value than planting

lower the site quality. Again, net present value is determined both by planting density and harvest age, and it is for site quality G11 optimal with lower planting density and earlier harvest than at the better sites. Also, as mentioned above, natural regeneration gives higher net present value than planting with CO_2 prices of € 0 and 5 per ton. For planting, no value on CO_2 makes the lower limit on planting density binding. Otherwise, optimal forest management follows the same pattern with increasing planting density and harvest age as the price on CO_2 increases.

The results for a real rate of return of 4% p.a. are shown in Fig. 2 and Table 3. Fig. 2 shows the relationship between number of plants per ha and net present value. Comparing this figure to the results for a real rate of return of 2% p.a. in fig.1, the net present value of the sites is lower, as higher real rate of return makes future income from timber harvest and carbon fixation weigh less. This also explains why natural regeneration is the current recommended management on all site qualities (CO_2 price € 0 per ton), and why optimal planting densities are lower than with 2% p.a. real rate of return. Future income from carbon benefit and timber does not cover the cost of planting. A value on CO_2 of € 10 per ton or more makes planting the best regeneration option at site quality G17. At site quality G14, planting is the best option with a value on CO_2 of € 15 per ton or more, and at site quality G11 with the highest value on CO_2 of € 41 per ton. In line with economic theory optimal harvest age is shorter than for 2% p.a. real rate of return (Table 3), except for the alternatives where natural regeneration is the best option.

4 Discussion

Positive prices of carbon benefits increase the value of the forest sites substantially. This is because there is a steady flow of income from carbon fixation from year 1. The fixated carbon is later released, from dead wood, harvest residues, soil, or wood products, but this release is gradual and happens late in the planning period. Starting with bare forest land and using positive real rates of returns, the revenues from fixation of carbon will be much larger than the cost from release of carbon. Conversely, traditional revenue from forestry consists of an investment cost in silviculture and incomes from timber harvests much later in the planning period. Compared to the steady flow of income from carbon fixation from year 1 and onwards the income from timber is small. For these reasons, the contribution from traditional forestry to total revenue decreases with increasing value of carbon benefits and with increasing real rates of returns. With high prices on CO_2, high real rates of returns, and/or low site qualities, it is optimal to let the revenue from forestry be low or negative so that most of the income is from carbon benefit. This result is in line with Solberg (1997).

The cost of planting is debited timber revenue. If this cost was split between carbon and timber, revenue from carbon benefit would become lower and revenue from timber production higher. However, the general result showing that timber production does not contribute much to total revenue with high CO_2-prices and real rates of returns would still hold.

The results show that even low prices per ton CO_2, for instance € 5–15 per ton, would make planting profitable in many of the situations were it is not profitable today. A price in this range would make planting profitable on site quality G17 and G14 for real rate of return 4% p.a., and on site quality G11 with real rate of return 2% p.a.

Optimal number of plants per ha increases with increasing CO_2 price. More plants per ha give higher annual growth and income from carbon fixation. Even though the higher carbon fixation will eventually be released, these emissions weigh less than the fixation early on with positive real rates of returns, as discussed above. A value on carbon benefit supports higher investment in planting. Optimal number of plants per ha changes a lot from the present situation with positive values of CO_2. With the highest price of CO_2 of € 41 per ton, the assumed maximum limit of 4000 plants per ha is optimal in all alternatives where substitution effects are not included. When substitution effects are included it is optimal with lower planting density and earlier harvest.

We have not simulated higher planting densities than 4000 plants per ha. For the highest price of CO_2 of € 41 per ton, we do not necessarily reach the optimal point because our constraint on maximum number of plants per ha becomes binding. With higher planting densities than this, the standing volumes may be so high that our growth and mortality functions are not valid.

A positive value on carbon benefit makes increased harvest age favourable. There are two reasons for this: first, longer rotation gives more years of carbon fixation, second, emissions from dead wood, harvest residues, soil, and wood products are postponed. With high prices on CO_2, the harvest age is up to 140 years. Just like we have chosen an upper limit on planting density, our choice of length of simulation period effectively makes 140 years an upper limit on harvest age.

Again, we have done this to keep growth and mortality within reasonable accuracy. The growth and mortality functions are based on empirical data for younger stands, and are likely to overestimate growth and underestimate mortality with increasing age and large growing stocks.. As such, our results for both optimal planting density and harvest age indicate that more research should be done on growth and mortality of old forest stands with large growing stocks.

Only planted spruce trees are included in the analyses. In real life there will be some natural regeneration in addition to the planted trees, especially natural regeneration of birch can be quite large. Therefore, the net present values of the forest sites are most likely underestimated in our analyses. On the other hand, depending on expected time before seedlings from natural regeneration start growing, high probability for good natural regeneration might decrease the optimal number of planted spruce trees per ha. A vital factor in this respect would be the minor vegetation, which is indirectly included since the study is assumed to cover typical site classes for Norway spruce stands. However, minor vegetation is not included in the carbon accounting model, because carbon in understory vegetation is not stored very long. In terms of carbon flows, Seely et al. (2002) found that minor vegetation had no influence on carbon flows in their study of white spruce, trembling aspen, and lodgepole pine stands in British Columbia.

Neither release thinning nor thinning were chosen in any of the optimal alternatives, independent of number of plants per ha, real rates of return, and price of CO_2. This is in line with current management, and previous optimisation analyses in Norway (e.g. Solberg and Haight 1991), because increased growth from thinning in Norwegian spruce stands does not increase sufficiently to cover the cost of these management options. For Finnish conditions, Pohjola and Valsta (2007) found that thinnings were optimal also with a carbon price of € 20 per ton CO_2. They also found that optimal harvest age increased with increasing price of CO_2, but not as much as in our analysis. The difference between the two studies is interesting. One explanation is of course, as mentioned above, different growth and yield functions. Another explanation is how carbon is accounted for. Pohjola and Valsta (2007) assume that all carbon is released immediately when timber is harvested, while we have assumed that some of the carbon is stored for a while in wood products and harvest residues. This would imply lower harvest age in our study. On the other hand, Pohjola and Valsta (2007) have not included carbon in belowground biomass. Including release of carbon from roots, stumps, and soil makes harvest less favourable with a price on CO_2.

Including saved greenhouse gas emissions from use of wood products and wood energy does as expected lower the optimal harvest age. There is, however, not much effect on planting density. The results show that it gives a higher net present value to use the same planting density but harvest earlier when substitution effects are taken into account. Including substitution effects will in principle make thinnings more favourable, since thinning gives the additional effect of increasing the share of sawn timber and thereby the total substitution effect. However, with high prices of CO_2 this additional substitution effect will be low compared to revenue from carbon fixation in the trees, and is also lower the higher the real rate of return.

In the model, sawn wood is used for a range of products, e.g. construction materials, plywood, and pallets. Pulpwood is used for paper and pulp. This product mix is exogenously determined. Using all sawn wood and pulpwood for energy would give a higher substitution effect than the product mix assumed in the model, but would move release of carbon from wood products closer in time. Determining use of wood endogenously in the model might lower optimal harvest age more than shown in our study when substitution effects are included, although the effect in our opinion is likely to be small with positive real rates of return.

All prices are deterministic in the model. In real life timber prices and costs fluctuate over time and forest owners may profit from such fluctuations. However, in long term comparative analyses like ours, we may realistically assume that the possibilities for adapting to timber price changes are equal for the forest management alternatives considered, assuming no long term upward or downward trends. The model is also deterministic when it comes to mortality of trees. In reality, and especially with climate change, there are also catastrophic events. Taking this into account might make postponing harvest and very high planting densities less favourable as old dense stands are more vulnerable.

Our analysis does not include effects of climate change as the model is based on empirical growth and yield functions. Earlier research has shown an increase in forest productivity due to increased temperature and precipitation, e.g. Karjalainen (1996c), Pussinen et al. (2002), Briceno-Elizondo et al. (2006), and Garcia-Gonzalo et al. (2007a, b). A study of Scots pine stands in Finland shows that the optimal rotation based on soil expectation value is 15 years shorter with 1% p.a. discount rate and 5 years shorter with 3% p.a. discount rate when effects of climate change are taken into account (Pussinen et al. 2002). In terms of carbon storage, previous research has showed both increase and decrease depending on climatic conditions, tree species, and forest management (e.g. Karjalainen 1996c). While increased productivity gives quicker and higher fixation of carbon, release of carbon from decaying wood, litter, and harvest residues also happens faster.

In our model, only the soil model, YASSO, can incorporate changes in climatic conditions. We used a prediction of the climate in Norway in 2050 (RegClim 2001) to map the sensitivity of release of carbon from decay of dead wood and soil to climate change. This climate scenario predicts higher temperature and precipitation, which leads to quicker release of carbon from dead wood and soil. Physically, 1 ton of CO_2 in the form of dead wood is completely released again over the time period covered in the model (625 years). Because our model takes the time perspective into account by using discounting, the present value of 1 ton CO_2 in dead wood is lower than 1, and lower the slower decomposition takes place. In terms of present value, quicker release of carbon due to climate change makes release of carbon after harvest higher and will favour a longer rotation. RegClim (2001) has predicted a 1.2° C increase in annual average temperature for the period 2030–2050 and an increase in precipitation of 0.4 mm per day of the growing season, as an average for Norway. Running the YASSO model with these climatic conditions and a 2% p.a. discount rate increases the present value of release of CO_2 with 3–20% depending on dead wood category. However, the effect has to be discounted back to the present, and the increase in present value from incorporating climate change is 1–4 ton from 100 ton CO_2 in dead wood that starts decaying in 2050. Higher discount rates would give lower changes due to climate change, as future emissions are given lower weight. This sensitivity analysis is only for climate change impacts on how fast decomposition of dead wood takes place. With higher productivity there would also be more dead wood entering the soil and increased carbon fixation due to higher forest growth.

Higher mortality due to climate change would give a lower harvest age, as it makes harvest more favourable. Hoen and Solberg (1999) did a sensitivity analysis of how much the mortality rates influenced the net present value of the forest in Buskerud and Vestfold in Southeast Norway. In the analysis the objective function was to maximise total net present value with discount rates of 2, 3, 4, and 5% p.a. The general mortality rate was increased from 0.4% p.a. to 0.76% p.a., and for stands with more than 500 stems per ha the mortality rate was increased to 1.52% p.a. after a certain age limit (80–120 years). With a CO_2-price of € 0 per ton the net present value was 3–7% lower with increased mortality rates, whereas with a CO_2-price of about € 31 per ton the net present value was 6% lower. The simulation period was 30 years, so the difference would be larger for longer simulation periods where more of the stands would reach the age limit for increased mortality.

Our emphasis is not on forecasting carbon storage in forests, but on finding how forest management should or would change with a value on carbon. Including effects of climate change in this type of study is a very interesting topic for further research. Looking at only carbon fixation and release, the optimal rotation is at the time when value of fixation and value of delaying decay equals the interest on land and emission from additional growth (Hoen 1993). All these aspects will change with climate change. The main results from our analysis, which is that a value on carbon would make it optimal with postponement of harvest, higher investments in silviculture, and less thinnings, are consistent for all the alternatives we have analysed. Previous research including effects of climate change and our sensitivity analysis of release of carbon from dead wood, litter, and soil, indicate that these findings would still hold if moderate climate change was included, although the actual impacts on investment intensity and harvest age would of course change. Albedo is another important factor which is not included in our analysis. As pointed out in several studies (e.g. Betts 2000, Gibbard et al. 2005, Bala et al. 2007, Betts et al. 2007, Bonan 2008, Thompson et al. 2009, Schwaiger and Bird 2010, Arora and Montenegro 2011) albedo effects could play a decisive role regarding forest management for climate mitigation.

Monserud (2003) found that hybrid models are promising for including effects of climate change in forest management analyses, as they can take advantage of both the strengths of growth and yield models and the strengths of process-based physiological models. As discussed in for instance Kimmins (2008), models should be as simple as possible, but as complex as necessary. To find the proper balance here is the challenge. Also, the many uncertainty factors involved have to be considered in a consistent and realistic way, and in a forest management context. For that, cooperation between ecological and forest management modelling should be improved.

The forest serves many different purposes that might conflict with changed management due to positive prices of CO_2. For instance, increased rotation lengths and older stands are in principle beneficial for biodiversity, but very dense stands are not. Dense stands let little light down to the forest floor and the trees become thinner. In the future, it will be an interesting task to find forest management treatments which balance appropriately the various benefits from forests.

5 Conclusion

Given the assumptions of the study, with a positive value on carbon benefits from forests, optimal management of even aged Norway spruce will change from what is currently optimal. Planting will be better than natural regeneration in situations where it is not profitable today, it will be optimal to plant more trees per ha, and harvest age will be higher. Since planting density and harvest age are variables we can control, our results indicate that calculations of carbon benefits from forests based on current recommended management underestimate the forests' potential to provide this good.

Increasing prices on carbon benefit makes revenue from industrial wood harvest less important. With high prices of CO_2, forest management is mostly aimed at maximising the carbon benefit. Including saved greenhouse gas emissions from using wood products instead of more energy intensive materials and fossil fuels increases the net present value of the forest. It does not influence the optimal number of plants per ha much, but leads to shorter rotation lengths.

This study includes many uncertain factors, and one should be careful in making forest management recommendations based only on our results. The largest uncertainties are in our opinion related to the accuracy of the forest growth and mortality functions at high planting density, large growing stock and old ages, and that albedo and future climate changes are not considered. As such, the analyses presented should be viewed as exploratory and not normative.

Further research should focus on several issues to improve this type of analyses. First, it is important to get more reliable functions for growth and mortality in forests with high planting densities, large growing stocks and high age. Equally important is to improve the knowledge about how much these factors are affected by possible future climate changes. Here, combinations of process modelling and traditional modelling using empirical functions seem necessary. Another important aspect is to estimate the trade offs between carbon benefit and other non wood forest services.

References

Arora, V.K , Montenegro, A. 2011. Small temperature benefits provided by realistic afforestation efforts. Nature Geoscience 4: 514–518.

Ågren, G.I. & Hyvönen, R. 2003. Changes in carbon stores in Swedish forest soils due to increased biomass harvest and increased temperatures analysed with a semi-empirical model. Forest Ecology and Management 174: 25–37.

Backéus, S., Wikström, P. & Lämås, T. 2005. A model for regional analysis of carbon sequestration and timber production. Forest Ecology and Management 216: 28–40.

— , Wikström, P. & Lämås, T. 2006. Modeling carbon sequestration and timber production in a regional case study. Silva Fennica 40(4): 615–629.

Bala, G., Caldeira, K., Wickett, M., Phillips, T.J., Lobell, D.B., Delire, C. & Mirin, A. 2007. Combined climate and carbon-cycle effects of large-scale deforestation. PNAS 104: 6550–6555.

Betts, R.A. 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. Nature 408: 187–190.

— , Falloon, P.D., Goldweijk, K.K. & Ramankutty, N. 2007. Biogeophysical effects of land use on climate: model simulations of radiative forcing and large-scale temperature change. Agricultural and Forest Meteorology 142: 216–233.

Bonan, G.B. 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320: 1444–1449.

Blingsmo, K.R. & Veidahl, A. 1992. Functions for gross price of standing spruce and pine trees. Research Paper of Skogforsk 8/92. 23 p. [In Norwegian with English summary].

Børset, O. 1985a. Forest ecology (Skogøkologi). Landbruksforlaget, Oslo, Norway.

— 1985b. Forest management (Skogskjøtsel). Landbruksforlaget, Oslo, Norway.

Briceno-Elizondo, E., Garcia-Gonzalo, J., Peltola, H., Matala, J. & Kellomäki, S. 2006. Sensitivity of growth of Scots pine, Norway spruce and silver birch to climate change and forest management in boreal conditions. Forest Ecology and Management 232: 152–167.

Chen, W., Chen, J.M., Price, D.T., Cihlar, J. & Liu, J. 2000. Carbon offset potentials of four alternative forest management strategies in Canada: a simulation study. Mitigation and Adaption Strategies for Global Change 5: 143–169.

Eid, T. & Øyen, B.-H. 2003. Models for prediction of mortality in even-aged forest. Scandinavian Journal of Forest Research 18: 64–77.

Ericsson, E. 2003. Carbon accumulation and fossil fuel substitution during different rotation scenarios. Scandinavian Journal of Forest Research 18: 269–278.

Fankhauser, S. 1994. The social cost of greenhouse gas emissions: an expected value approach. The energy journal 15(2): 157–184.

Garcia-Gonzalo, J., Peltola, H., Gerendiain, A.Z. & Kellomäki, S. 2007a. Impacts of forest landscape structure and management on timber production and carbon stocks in the boreal forest ecosystem under changing climate. Forest Ecology and Management 241: 243–257.

Garcia-Gonzalo, J., Peltola, H., Briceno-Elizondo, E. & Kellomäki, S. 2007b. Changed thinning regimes may increase carbon stock under climate change: a case study from a Finnish boreal forest. Climatic Change 81: 431–454.

Gibbard, S.G., Caldeira, K., Bala, G., Phillips, T.J., Wickett, M. 2005. Climate effects of global land cover change. Geophysical Research Letters 32(23).

Hoen, H.F. 1993. The Faustmann rotation in the presence of a positive CO_2-price. Scandinavian forest economics, Gilleleje, Denmark.

— & Solberg, B. 1994. Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. Forest Science 40(3): 429–451.

— & Solberg, B. 1999. Policy options in carbon sequestration via sustainable forest management: an example from the North. In Palo, M. (ed): Forest transitions and carbon fluxes. The United Nations University, World Institute for Development Economics Research. 15: 117–132.

— , Eid, T., Veisten, K. & Økseter, P. 1998. Financial implications of conserving biodiversity in forests. Assumptions and method (Økonomiske konsekvenser av tiltak for et bærekraftig skogbruk. Forutsetninger og metodebeskrivelse). Rapport fra skogforskningen – Supplement 1998(6). Ås, Norway.

IPCC 2001. Land use, land-use change and forestry. A special report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC 2007a. Climate change 2007 – The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge University Press.

IPCC 2007b. Climate change 2007 – Mitigation of climate change. Contribution of Working Group III to the Fourth Assessment Report of the IPCC. Cambridge University Press.

Karjalainen, T. 1996a. Dynamics and potentials of carbon sequestration in managed stands and wood products in Finland under changing climatic conditions. Forest Ecology and Management 80: 113–132.

— 1996b. Model computations on sequestration of carbon in managed forests and wood products under changing climatic conditions in Finland. Journal of Environmental Management 47: 311–328.

— 1996c. The carbon sequestration potential of unmanaged forest stands in Finland under changing climatic conditions. Biomass and Bioenergy 10: 313–329.

Kimmins, J.P. 2008. From science to stewardship: harnessing forest ecology in the service of society. Forest Ecology and Management 256: 1625–1635.

Lappi, J. 2005. J-user's guide. Version 0.9.4, February 2005. Finnish Forest Research Institute, Suonenjoki Research Station.

Li, Z., Kurz, W.A., Apps, M.J. & Beukema, S.J. 2003. Belowground biomass dynamics in the carbon budget model of the Canadian forest sector: recent improvements and implications for the estimation of NPP and NEP. Canadian journal of forest research 33: 126–136.

Liski, J., Pussinen, A., Pingoud, K., Mäkipää, R. & Karjalainen, T. 2001. Which rotation length is favourable to carbon sequestration? Canadian journal of forest research 31: 2004–2013.

— , Palosuo, T., Peltoniemi, M. & Sievänen. R. 2005. Carbon and decomposition model YASSO for forest soils. Ecological Modelling 189(1–2): 168–182.

Lunnan, A., Navrud, S., Rørstad, P.K., Simensen, K. & Solberg, B. 1991. Potential of forests and forestry to prevent accumulatio of CO_2 in the atmosphere (Skog og skogproduksjon i Norge som virkemiddel mot CO_2-opphopning i atmosfæren). Aktuelt fra skogforsk 6. Department of Forest Sciences, Agricultural University of Norway. Ås, Norway.

Marklund, L.G. 1988. Biomass functions for pine, spruce and birch in Sweden (Biomassafunktioner för tall, gran och björk i Sverige). Sveriges lantbruksuniversitet, Report 45. Umeå, Sweden.

Monserud, R.A. 2003. Evaluating forest models in a sustainable forest management context. FBMIS (Forest Biometry, Modelling and Information Sciences) 1: 35–47.

Pohjola, J. & Valsta, L. 2007. Carbon credits and management of Scots pine and Norway spruce stands in Finland. Forest Policy and Economics 9: 789–798.

Price, D.T., Halliwell, D., Apps, M.J., Kurz, W.A. & Curry, S. 1997. Comprehensive assessment of carbon stocks and fluxes in a Boreal-Cordilleran forest management unit. Canadian journal of forest research 27: 2005–2016.

Pussinen, A., Karjalainen, T., Mäkipää, R., Valsta, L. & Kellomäki, S. 2002. Forest carbon sequestration and harvests in Scots pine stand under different climate and nitrogen deposition scenarios. Forest Ecology and Management 158: 103–115.

Raymer, A.K.P., Gobakken, T., Solberg, B., Hoen, H.F. & Bergseng, E. 2009. A forest optimisation model including carbon flows: Application to a forest in Norway. Forest Ecology and Management 258: 579–589.

RegClim 2001. The climate in Norway in 50 years (Klimaet i Norge om 50 år).

Richards, K.R. & Stokes, C. 2004. A review of forest carbon sequestration cost studies: a dozen years of research. Climatic Change 63: 1–48.

Schlamadinger, B. & Marland, G. 1996. The role of forest and bioenergy strategies in the global carbon cycle. Biomass and Bioenergy 10(5/6): 275–300.

Schwaiger, H.P & Bird, D.N. 2010. Integration of albedo effects caused by land use change into climate balance: Should we still account in greenhouse gas units? Forest Ecology and Management 260: 278–286.

Seely, B., Welham, C. & Kimmins, H. 2002. Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. Forest Ecology and Management 169: 123–135.

Shvidenko, A., Nilsson, S. & Roshkov, V. 1997. Possibilities for increased carbon sequestration through the implementation of rational forest management in Russia. Water, Air, and Soil Pollution 94: 137–162.

Solberg, B. 1997. Forest biomass as carbon sink – economic value and forest management/policy implications. In Economics of carbon sequestration in forestry. Critical reviews in environmental science and technology. 27: 323–333.

— & Haight, R.G. 1991. Analysis of optimal economic management regimes for Picea abies stands using a stage-structured optimal-control model. Scandinavian Journal of Forest Research 6: 559–572.

Thompson, M.P., Adams D. & Sessions, J. 2009. Radiative forcing and the optimal rotation age. Ecological Economics 68: 2713–2720.

Tol, R.S.J. 2005. The marginal damage costs of carbon dioxide emissions: and assessment of the uncertainties. Energy Policy 33: 2064–2074.

Tveite, B. 1977. Site index curves for Norway spruce (Picea abies (L.) Karst.). [In Norwegian with English summary]. Norwegian Forest Research Institute. Report 33(1). Ås, Norway.

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Appendix. The results for real rate of return 3% p.a. are shown in Table A.1 and Fig.A.1, and the results for real rate of return 5% p.a. are shown in Table A.2 and Fig.A.2. Figs. A.1 and A.2 show the relationship between number of plants per ha and net present value. Comparing these figures to the results for real rates of return of 2 and 4% p.a. in Fig.1 and Fig 2, the net present value of the sites is lower the higher the real rate of return. Tables A.1 and A.2 give net present value, planting density, and harvest age for the optimum of the curves. Again, comparing these results with those for real rate of return of 2 and 4% p.a. (Tables 2 and 3) reinforces the general results of lower planting densities and earlier harvest age the higher the real rate of return. Natural regeneration is also more favourable the higher the real rate of return.

Table A.1. Maximum net present value and the corresponding planting density and harvest age with 3% p.a. real rate of return.

		Price CO_2 (€ per ton)					
		0	5	10	15	20	41
Site quality G17 without substitution							
NPV (€ per ha)	Total	494[1]	1182	1947	2878	3912	9284
	Timber	494	454	160	–80	–336	–1602
	CO_2	0	729	1787	2958	4248	10886
Plants per ha		1100	1500	2000	2200	2400	4000
Harvest age (years)		70	80	90	100	110	140
Site quality G17 with substitution							
NPV (€ per ha)	Total	494[1]	1264	2113	3097	4159	9547
	Timber	494	454	224	–1	–304	–1543
	CO_2	0	810	1889	3099	4462	11091
Plants per ha		1100	1500	2000	2200	2500	4000
Harvest age (years)		70	80	85	95	105	135
Site quality G14 without substitution							
NPV (€ per ha)	Total	229[1]	708	1357	2162	3043	7502
	Timber	229	101	–162	–357	–626	–1664
	CO_2	0	607	1519	2519	3670	9168
Plants per ha		800	1500	1900	2100	2300	4000
Harvest age (years)		80	85	100	110	125	140
Site quality G14 with substitution							
NPV (€ per ha)	Total	229[1]	767	1463	2307	3203	7728
	Timber	229	101	–162	–300	–452	–1664
	CO_2	0	666	1625	2607	3654	9393
Plants per ha		800	1500	1900	2100	2300	4000
Harvest age (years)		80	85	100	105	110	140
Site quality G11 without substitution							
NPV (€ per ha)	Total	–211[1]	–12[1]	210[1]	528[1]	902	2848
	Timber	–211	–226	–245	–594	–594	–1885
	CO_2	0	215	455	1122	1496	4731
Plants per ha		800	800	800	1500	1500	4000
Harvest age (years)		100	115	130	140	140	140
Site quality G11 with substitution							
NPV (€ per ha)	Total	–211[1]	2[1]	231[1]	566[1]	950	2974
	Timber	–211	–219	–245	–578	–594	–1885
	CO_2	0	221	477	1145	1544	4859
Plants per ha		800	800	800	1500	1500	4000
Harvest age (years)		100	110	125	135	140	140

[1] Natural regeneration gives a higher net present value than planting

Table A.2. Maximum net present value and the corresponding planting density and harvest age with 5% p.a. real rate of return.

		Price CO_2 (€ per ton)					
		0	5	10	15	20	41
Site quality G17 without substitution							
NPV (€ per ha)	Total	–196[1]	–13[1]	179[1]	470	811	2602
	Timber	–196	–199	–211	–531	–583	–1964
	CO_2	0	186	390	1001	1394	4567
Plants per ha		800	800	800	1500	1500	4000
Harvest age (years)		60	65	75	80	90	140
Site quality G17 with substitution							
NPV (€ per ha)	Total	–196[1]	–2[1]	199[1]	506	851	2619
	Timber	–196	–199	–211	–507	–531	–1916
	CO_2	0	197	410	1013	1382	4535
Plants per ha		800	800	800	1500	1500	4000
Harvest age (years)		60	65	70	75	80	115
Site quality G14 without substitution							
NPV (€ per ha)	Total	–264[1]	–116[1]	45[1]	215[1]	473	1839
	Timber	–264	–274	–294	–306	–652	–1121
	CO_2	0	158	339	521	1126	2960
Plants per ha		800	800	800	800	1500	2300
Harvest age (years)		70	75	80	90	100	140
Site quality G14 with substitution							
NPV (€ per ha)	Total	–264[1]	–108[1]	57[1]	231[1]	496	1850
	Timber	–264	–267	–284	–294	–620	–1101
	CO_2	0	159	341	525	1116	2952
Plants per ha		800	800	800	800	1500	2300
Harvest age (years)		70	75	80	85	90	125
Site quality G11 without substitution							
NPV (€ per ha)	Total	–369[1]	–304[1]	–235[1]	–163[1]	–88[1]	276[1]
	Timber	–369	–710	–716	–1026	–1133	–1980
	CO_2	0	112	232	446	634	1800
Plants per ha		800	800	800	800	800	1500
Harvest age (years)		90	100	110	120	135	140
Site quality G11 with substitution							
NPV (€ per ha)	Total	–369[1]	–302[1]	–232[1]	–160[1]	–86[1]	280[1]
	Timber	–369	–710	–716	–1019	–1125	–1980
	CO_2	0	115	236	444	630	1804
Plants per ha		800	800	800	800	800	1500
Harvest age (years)		90	95	105	115	125	140

[1] Natural regeneration gives a higher net present value than planting

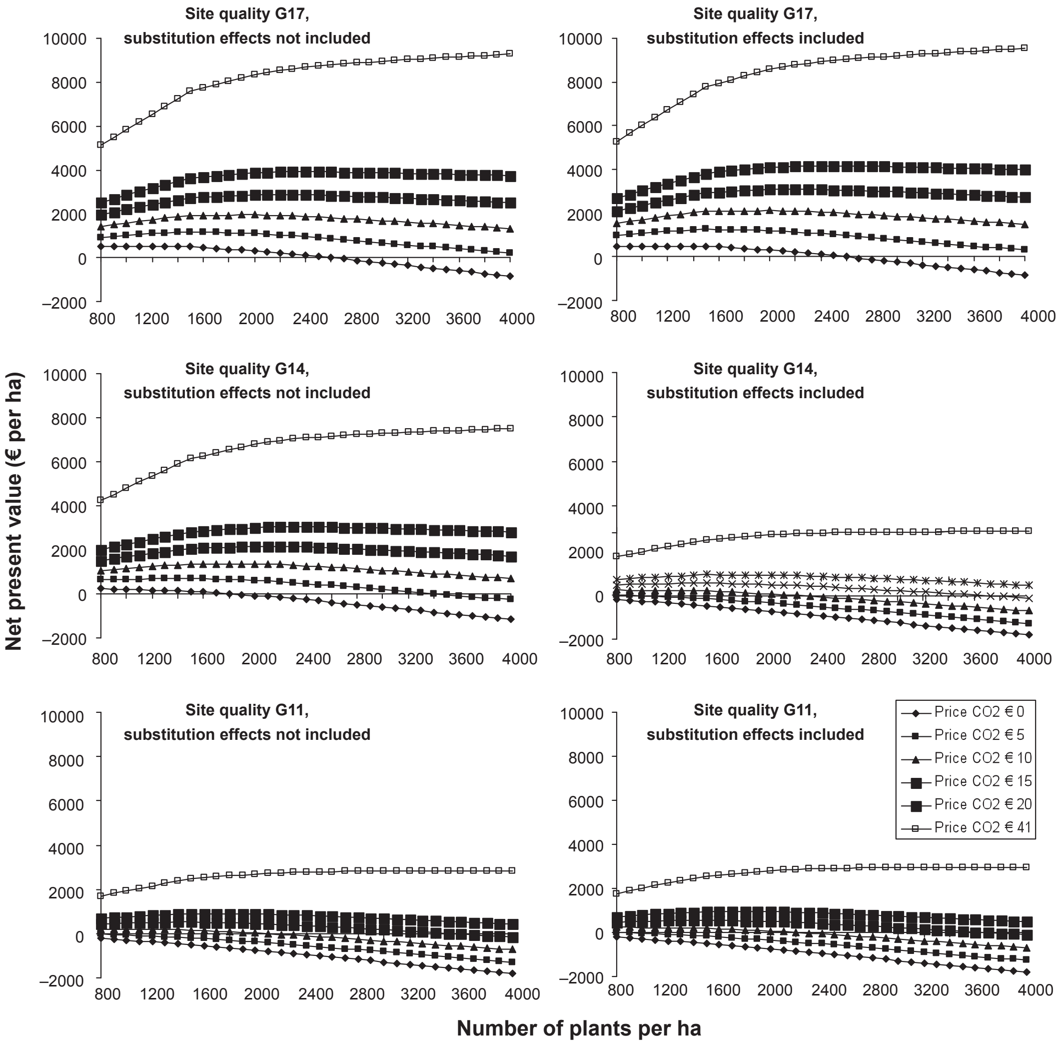

Fig. A.1. Net present value as a function of planting density with 3% p.a. real rate of return, for site qualities G11, G14, and G17, with and without substitution effects, and six different CO_2 prices.

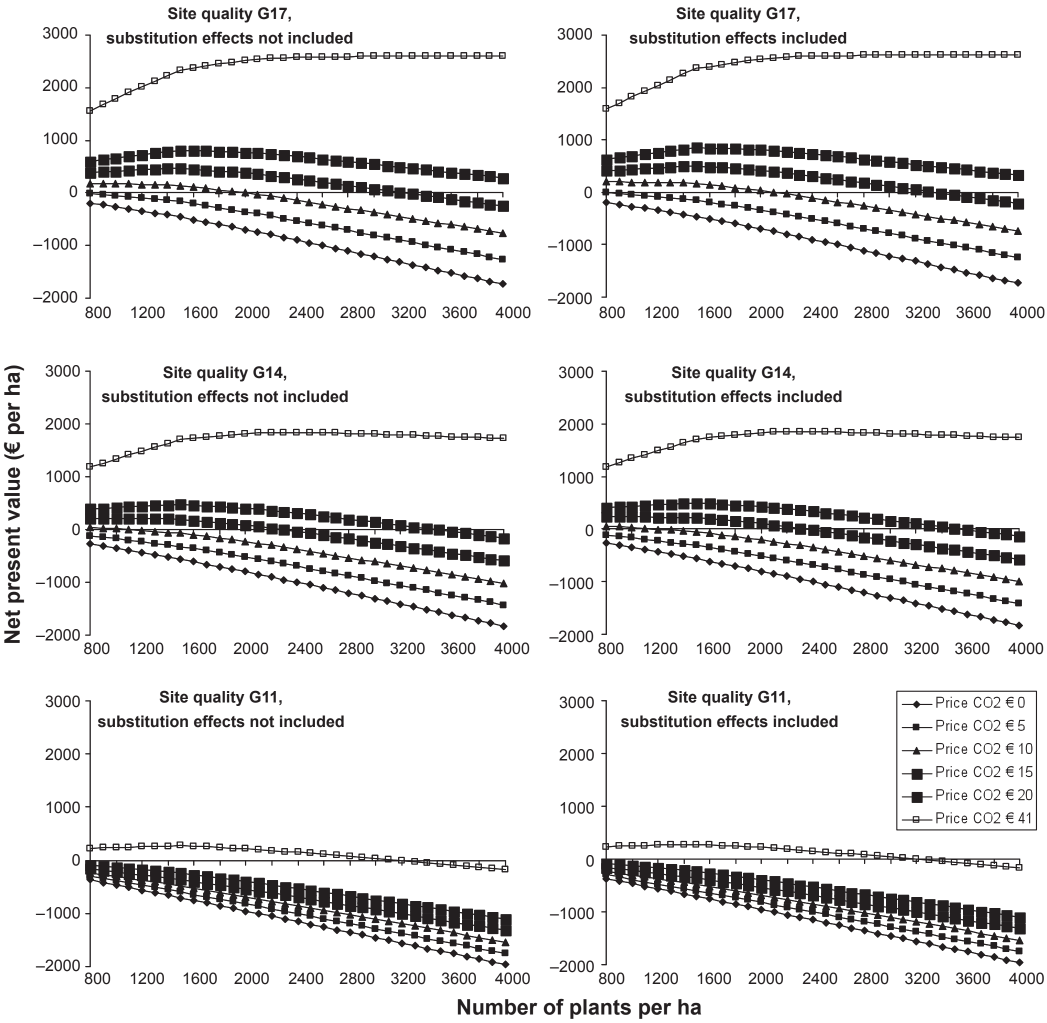

Fig. A.2. Net present value as a function of planting density with 5% p.a. real rate of return, for site qualities G11, G14, and G17, with and without substitution effects, and six different CO_2 prices.