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Complete List of Authors:	Lundmark, Tomas ; Swedish University of Agricultural Scien, Poudel, Bishnu; Linneuniversitet Fakulteten for Teknik, Department of Forestry and Wood Technology; Stål, Gustav; Swedish University of Agricultural Scien, Department of forest management and ecology; Nordin, Annika; Swedish University of Agricultural Sciences, Department of Forest Genetics and Plant Physiology, Umeå Plant Science Centre Sonesson, Johan; The Forestry Research Institute of Sweden (Skogforsk),
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Tomas Lundmark, Bishnu Chandra Poudel, Gustav Stål, Annika Nordin, Johan Sonesson

Tomas Lundmark
Department of Forest Ecology and Management,
Swedish University of Agricultural Sciences,
901 83 Umeå Umeå, Sweden,
Telephone: +46 70-631 74 12
Fax: +46 90-786 81 25
e-mail: tomas.lundmark@slu.se

Bishnu Chandra Poudel
Department of Forestry and Wood Technology,
Linnaeus University,
351 95, Växjö Sweden,
e-mail: bishnu.poudel@lnu.se

Gustav Stål
Department of Forest Ecology and Management,
Swedish University of Agricultural Sciences,
901 83 Umeå, Sweden,
e-mail: gustav.stal@slu.se

Annika Nordin
Department of Forest Genetics and Plant Physiology,
Umeå Plant Science Centre, Swedish University of Agricultural Sciences,
901 83, Umeå, Sweden,
e-mail: annika.nordin@slu.se

Johan Sonesson
Skogforsk, Uppsala Science Park, 7
51 83 Uppsala, Sweden,
e-mail: johan.sonesson@slu.se

Abstract

The choice of a rotation length is an integral part of even-aged forest management regimes. In this study, we have simulated stand development and carbon pools in four even-aged stands representing the two most common tree species in Fennoscandia, Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), growing on high and low productive sites. We hypothesized that increased rotation lengths (+10, +20 and +30 years) in comparison with today's practice would increase forests' average carbon stock during a rotation cycle, but decrease the average yield. The results showed that for spruce a moderate increase in rotation length (+10 years) increased both average standing carbon stock and average yield. For the longer alternatives (+20 and +30 years) for spruce and for all pine alternatives prolonging rotation lengths resulted in increased average standing carbon stocks but decreased average yield resulting in decreased carbon storage in forest products and decreased substitution effects. Decreasing the rotation lengths (-10 years) always resulted in both decreased average standing carbon stocks and decreased yields. We conclude that a moderate increase of rotation lengths may slightly increase forests' climate benefits for spruce sites but for all other alternatives there was a trade-off between the temporary gain of increasing carbon stocks and the permanent loss in productivity and consequently substitution potential.

Keywords: Net present value, land expectation value, forest management, climate benefit

Introduction

Forests contributes to climate change mitigation when atmospheric carbon is assimilated by trees and other vegetation resulting in a net ecosystem production that can be described as the long-term carbon-sequestration by ecosystems (Luyssaert et al 2007). Net ecosystem production is the actual carbon sink strength of the forest ecosystem. In a managed forest system the accumulated carbon can be stored in the forest to increase the carbon stock and/or harvested for consumption. When forest-based products substitute products with a fossil origin or products with high process emissions such as cement manufacturing society's addition of fossil carbon to the atmosphere is reduced. To estimate forestry's full effect on the CO_2-concentration in the atmosphere both the effect of carbon stock changes in the forest ecosystem and substitution effects including carbon stock changes in forest based products should be considered simultaneously. When substitution effects are estimated not only avoided emissions due to the replacement of fossil based products and energy intensive materials with renewable forest based products should be considered but also emission related to management practices and processing of the harvested wood (Lundmark et al. 2016, Braun et al. 2016).

Fennoscandia is characterized by a long history of even-aged forest management, the majority of productive forestland having been actively managed for wood production for at least a century. Also in many other forest countries this is the dominating silvicultural system with the aim to have an even age class distribution across the landscape to allow a steady flow of timber from the forest to the industry (Filip et al. 2000; Nordin and Sandström 2016). Tree growth of such managed even-aged stands follows a pattern whereby the current annual increment (CAI) increases after stand establishment, peaks when maximum leaf area is attained to thereafter decline (Assmann 1970). The CAI curve and the resulting mean annual increment (MAI) curve (i.e. average annual increment since stand establishment) have shapes that vary according to tree species and site conditions. The two curves intersect where the MAI culminates. According to theory this is the best time for harvesting a stand if the aim is to maximize average wood volume production. However, forest management decisions are not only driven by wood volume considerations, but also by economy and other factors (Roberge et al. 2016). In Fennoscandia profitability and evenness of revenues are guiding principles (Brukas and Weber 2009) and managers normally apply standard investment analyses techniques in scheduling silvicultural activities, typically using a discount rate of 2-3%. By optimisation of the forestland's net present value at these levels of interest, the rotation length, i.e. the time period elapsed between two final fellings, for a stand normally become shorter than if average wood volume production would be maximized (Hyytiäinen and Tahvonen 2002; Näslund 1969).

This practice may be challenged, as climate change mitigation becomes an additional concern to consider in silvicultural decisions. It has been claimed that longer rotations increasing the average carbon stock in stands also increase the overall climate benefit of forestry (Ekholm 2016; Kaipainen et al. 2004; Liski et al. 2001; Zanchi et al. 2014). The likely positive effects of longer rotations on forests' climate change mitigation potential may, however, be counteracted by reduced harvesting if MAI is reduced which in turn leads to lowered substitution effects (Ericsson 2003, Hector et al. 2016). To understand the effects of altered rotation lengths on forests' climate change mitigation potential both the effects on carbon stocks in the forest and in forest products as well as on substitution in society have to be considered simultaneously. In this paper we evaluate the effect of varied rotation length, in relation to a reference rotation length where economic value has been optimized for the site and the tree species growing at the site. The analyses are at the stand level and comprise two site fertility classes (rich and poor) and two tree species Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). We use a comprehensive modeling approach to describe forest growth and yield from stand establishment to the final harvest for different rotation lengths. The analyses include economic value and carbon stock changes in forest biomass, soil carbon and forest-based products as well as substitution effects.

Materials and methods

Study sites

We have simulated stand development and carbon pools in four even-aged stands representing the two most common tree species in Fennoscandia, Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), growing on high and low productive sites. Site index determined by dominant tree height at the age of 100 years (Hägglund 1972; Hägglund 1974) was used to describe the fertility of the sites. The high productive sites represented a site index of 30 m for Norway spruce (G30) and 24 m for Scots pine (T24) while corresponding figures for the low productive sites where 18 m (G18) and 16 m (T16) (Table 1). The site indices represent approximately the 25th and the 75th percentile of plot site index in the Swedish national forest inventory (NFI) for the two species respectively. The lower site indices typically found on high latitude and/or altitudes and the higher site indices at lower latitudes and altitudes. Pine sites are typically dry or mesic on coarse texture soils and spruce sites mesic or moist on fine texture soils.

Simulation of stand development

The simulations were made using the Heureka software package, which is the most developed and used simulation, planning and optimization tool for forests in Sweden (Wikström et al. 2011a). Heureka can be downloaded free of charge from [http://heurekaslu.org/wiki/Heureka_Wiki,](http://heurekaslu.org/wiki/Heureka_Wiki) where more information about the software can be found. The Heureka default models for growth of stands and individual trees are empirical and based on data from the Swedish National Forest Inventory (NFI) (Fahlvik et al. 2014). Stand growth, stand basal area and individual tree diameter are simulated for five-year periods. At the end of each five-year period, individual tree diameters are adjusted to sum up to the stand basal are given by the stand-level function. At the stand level, the model simulates total five-year basal are growth ($m^2 ha^{-1}$) for all tree species. At the single tree level, separate models provide five-year diameter growth rates for different tree species. Both models are empirical and generate growth based on variables describing the site, the stand as well as individual tree diameter and age. Both the stand and individual tree growth models have been validated by Fahlvik et al. (2014), who demonstrated that the model outcomes fit well with observed tree growth. Potential height growth is modeled for individual trees using the functions for top-height trees (Elfving and Kiviste 1997). Thereafter, height growth is reduced with competition modifier depending on the basal area of trees larger than the subject tree. Tree diameter and height are used to estimate stem volume (Brandel 1990) and the volume of single trees are summed up to per hectare values. Mortality due to self-thinning at high stand densities as well as damaging agents such as storms and insects are considered by the mortality model of Fridman and Ståhl (2001) .

Simulation of carbon pools

In Heureka, carbon in living trees is calculated using the biomass functions of Marklund (1988a) for stem, bark, branches and needles and functions of Petersson and Ståhl (2006) for stumps and roots. Carbon in soil is estimated using the Q-model (Rolff and Ågren 1999; Ågren and Hyvönen 2003), which simulates the decomposition of soil organic matter based on the continuous quality theory (Agren and Bosatta 1998), in which the soil organic matter is assumed to change continuously over time due to decomposition. In the model carbon input from litter is simulated based on tree growth and mortality. Stumps, roots, branches, and needles from harvested trees are also added to the soil carbon pool. The carbon pools in living trees and soil is calculated in the same five-year intervals as tree growth.

Optimization of management programs

The procedure for stand level optimization in Heureka computes a large number of management alternatives for each stand with respect to the timing of final felling and the number and timing of thinnings. In all cases thinning from below was simulated and the thinning intensity allowed to vary between 25 and 40% of the basal area. In both pine and spruce stands we assumed that 10% broadleaves (birch) is kept in the stand throughout the rotation to fulfill environmental certification standards. The different management programs computed were ranked according to their land expectation value (LEV) calculated according to Faustmann (1849) applying a discount rate of 2 % which is commonly used by Swedish forestry practice (Simonsen et al. 2010). The management program with the highest LEV was chosen as our reference rotation for each site.

Prices and costs

For the economic analysis, Heureka simulates bucking of the stems to sawlogs and pulpwood based on tree diameter and height. Timber prices from an up to date pricelist from the Swedish forest owner association were used. Pulpwood (dimeter 5-12 cm) price was 35 € per m^3 for all tree species. Sawlogs prices for pine and spruce increases with diameter from 12 cm up to 30 cm. The prices range from 35 to 90 € per m^3 for pine and from 35 to 60 € per m^3 for spruce.

Harvesting costs were calculated with functions based on productivity statistics from Swedish forestry (Brunberg 2012a, b). Per hour machine costs was set to 100 € for harvester in thinning and 110 € for harvester in final felling. For forwarder, the costs was 70 € and 80 € in thinning and final felling respectively. The cost for regeneration was set to 600 € ha^{-1} and for precommercial thinning to 250 € ha^{-1}.

<please place Table 1 about here>

For all sites, we started the simulations with a reference rotation starting from clearcut land with regeneration through planting of containerized seedlings. The aim of simulating this first rotation was to obtain starting values for soil carbon pool from the Q-model that were based on both site factors and forest management history. After clear-felling of the first rotation we simulated a set of five different rotations for each site; the reference rotation, one 10 years reduced and three prolonged rotations with 10, 20 and 30 years (Table 1). Output data on timber production, carbon pools and economy from these second rotations was used for our analyses of climate benefit and cost. To get an estimate of the cost for possible climate benefits obtained by altering rotations we calculated the net present value (NPV) for the different prolonged rotations at the time of decision to prolong rotations, which was assumed to be at the time when final felling was planned for the economically optimal reference scenarios for each species and site index. The NPV included the net revenue from final felling and the LEV for coming tree generations, assuming that the coming tree generations would continue to be managed with the prolonged rotation length. The reduction in NPV (cost) relative to the reference rotation was then divided by the additional climate benefit for each prolonged rotation alternative to get an estimate of the cost for the carbon benefit expressed as € per Mg carbon. This was done for each site, species and prolonged rotations with 10, 20 and 30 years.

Climate change mitigation potential

The potential of different forestland use strategies to mitigate climate change has to be evaluated relative to a base line scenario. In this study the baseline is the silvicultural program with optimal economic return, assumed to represent current forest practices. To mimic current forestry practice we also applied in the simulations the following assumptions; i) tops and branches as biofuel was extracted at final felling in the spruce stands, ii) when tops and branches were extracted 40% of the biomass in these fractions was left on the site, iii) at final felling ten trees per ha were retained for nature conservation purposes. We have then estimated carbon stock changes in standing forest biomass, forest soils and forest-based products as well as the substitution effect due to the use of forest-based products and bioenergy instead of fossil energy and fossil-based products. To evaluate the climate benefit of different silvicultural programs we have applied the concept of climate change mitigation efficiency (CCME) introduced by Lundmark et al. (2014) and Braun et al. (2016). CCME takes into account;

- Carbon stock changes in the forest ecosystem (including soil);
- Carbon stock changes in long-lived wood products (the model calculations use historical data taken from various statistical sources to establish initial pool sizes);
- Fossil emissions from forest management and logistics;
- Production emissions from the forest industry;
- Substitution effects through the avoidance of the production and disposal of (generally more energy-intensive) non-wood products;
- Substitution effects of avoided use of fossil fuels due to energy recovery from residues from final harvest, wood processing, chemical pulp processing, waste wood and paper.

CCME is expressed as the average CO_2 emissions reduction effect per cubic meter of harvested biomass. We assumed a CCME of 0.72 t CO_2 per m^3 of utilized wood representing a utilization strategy where large diameter stem-wood was used for production of wood construction material and small-diameter stem-wood and residues were used for energy. For further details see Lundmark et al. (2014).

To make the different rotation lengths comparable the climate change mitigation potential was described as the sum of average annual carbon stock changes (trees, soil and harvested wood products) and average annual substitution benefit over the full rotation for each of the different rotation lengths. The results for the altered rotation lengths were then compared to the reference rotation length where economic value was optimized for each site fertility class and tree species.

Results

The land expectation value (LEV) estimates the value of forestland excluding the value of the present timber. In the simulation of the reference scenario optimizing LEV gave a rotation length that varied between 75 and 115 years depending on tree species and site fertility (Table 1). Shortening (10 years) or prolonging (10, 20 or 30 years) the rotation length relative to this reference lowered LEV. In absolute terms, the largest reduction was found in the more fertile stands when rotation length was prolonged by 30 years (Fig 1).

Mean annual carbon stock in living biomass over a rotation increased when rotation length was prolonged 10-30 years relative to the reference, and decreased when rotation length was shortened 10 years. This was consistent for pine and spruce stands at high- as well as low productivity sites (Fig 1).

Prolonging the rotation length 20 and 30 years relative to the reference reduced mean annual increment, resulting in lowered substitution effects for both pine and spruce stands at high- as well as low productivity sites. Prolonging the rotation with 10 years resulted in a minor increase in substitution effects in the spruce stands and in a minor decrease in the pine stands. Shortening the rotation length 10 years generally gave only minor effects on substitution relative to the reference rotation (Fig 1).

The average annual carbon stock change in wood products and forest soil varied to a small extent between the different rotation periods and represented only a minor part of the total carbon balance in the different silvicultural alternatives that were studied (Fig 1).

<please place Figure 1 about here>

Altogether these variables can be added up to estimate the total climate benefit (increased climate change mitigation potential) in comparison to the reference scenario. This showed that a shortened rotation length of 10 years resulted in a negative climate benefit and lower economical outcome for all alternatives that were analyzed. The negative effect was larger for the high than the low productivity sites. For both low and high productivity pine sites, a small climate benefit of 20-92 kg C per hectare and year could be gained by prolonging the rotation length, but at a cost of decreased economic return. A larger climate benefit of 34-217 kg C per hectare and year was obtained when rotation length was prolonged for the spruce stands, but also here at a cost of decreased economic return. The largest climate benefit relative to the decrease in economic return was obtained at the low productivity sites where the loss in LEV in absolute terms was much smaller than for the high productivity sites (Fig 1, Tab 2).

<please place Table 2 about here>

Discussion

An actively managed forest landscape can contribute to climate change mitigation by sustainable provision of biomass while at the same time maintaining large standing forest carbon stocks (Nabuurs et al. 2007). In this study we investigate how altered rotation lengths in even-aged forest management may result in different climate benefits due to the complex interactions between silvicultural practice, carbon stored in the ecosystem and in forest-based products in society, and the amount of harvested biomass that results in substitution effects (Smyth et al. 2014). We show that in comparison with today's practice in Sweden, prolonging rotation lengths increases forests' average carbon stocks for both spruce and pine dominated stands. For spruce dominated stands prolonging rotations with ≤ 10 years increased the harvesting potential, while for pine it slightly decreased. Prolonging rotations > 10 years, however, decreased harvesting potential for both pine and spruce dominated stands.

The choice of a rotation length is an integral part of even-aged forest management regimes (Curtis 1997), and is dictated by the goals of forest management. Traditionally the main management goal has been the production of wood-based commodities such as sawlogs, pulpwood and biofuel. In this context, the optimal rotation has been dictated by economic drivers in interaction with factors influencing wood volume growth, such as tree species and site productivity. A number of studies have shown that longer rotations in comparison with today's practice increase the average carbon stock in stands and it has been suggested that this would increase forests' climate change mitiagtion potential (Kaipainen et al. 2004; Liski et al. 2001; Zanchi et al. 2014). These studies include carbon in standing biomass, soil and wood products, but not substitution effects and the effects on economic return when altering rotation lengths. Our simulation study support these previous studies as we show that the effect of prolonging the rotation length, relative to a reference scenario, increases forests' average carbon stocks over the rotation for both spruce and pine stands on high and low productivity sites (Fig 1). It is, however, important to consider that the effect of increasing carbon stocks at the stand level is related to the actual change in average carbon stock from one rotation to the next. This means that the effect will be temporary and restricted to the first new rotation (Hektor et al. 2016). During the following rotations the prolonged rotation will be the new reference and consequently there will be no further climate benefit since future average carbon stock will remain unchanged. Moreover, if substitution effects are also included in the estimation of climate benefits, our study highlights a difference between the two tree species. For spruce prolonging the rotation by 10 years had a positive effect on the harvesting potential and hence the substitution, while for pine a negative effect was found. This can be explained by species specific differencens in growth dynamics where current annual increment declines more slowly over time for spruce than for pine after maximum annual increment has been reached (Nilsson et al. 2010). The climate benefit gained from increased standing stocks when prolonging rotations for > 10 years was counteracted by reduced yield for both spruce and pine. This effect of prolonging rotations is well known and has been discussed earlier in terms of reduced climate benfit (Ericsson 2003; Hektor et al. 2016). Considering that the positive effects of increased carbon stock is temporary, while the substitution effects will be permanently lowered when rotations are prolonged it is evident that the positive climate benefit of prolonging rotations will be restricted to one rotation. During the following rotations the climate benefit will be negative due to the lower yield, and consequently lower substitution effects.

As the reference scenario was set up to optimise the net present value (NPV) all the scenarios with prolonged rotations resulted in decreased NPV. Hence, across the scenarios the climate benefits gained from prolonging the rotations resulted in a cost between 9 and almost 400€ per Mg C (Table 2). The most cost efficient alternative was for the low productivity spruce site where the cost per Mg C was 9€ (for the +10 years rotation) and 71€ (for the +30 years rotation). These costs can be compared with the carbon price in the trading market during 2016 that has varied between 15€ and 30€ per Mg C (https://www.eex.com/en#/en). Consequently, at present only the alternative with spruce on low productivity sites and a prolonged rotation of 10 years seems to be a market competitive alternative to mitigate climate change, although this would change if the price for carbon trading sharply increased.

In our study we also included one alternative where rotation length was shortened 10 years relative to the reference scenario. In a Swedish context this alternative appears timely as for example the largest forest owners association in southern Sweden has recommended their members to shorten rotations by 10-15 years in spruce dominated forest to decrease the risk of storm and root rot damage (Södra Skog 2012). Moreover the stateowned forest company Sveaskog has expressed a desire to be allowed to harvest some types of forest stands earlier than currently allowed by the law to compensate for ambitious set-asides of forest for conservation purposes (Fries et al. 2015). Our study shows that shorter rotations decrease both forest carbon stocks and the harvesting potential (and hence the substitution effect), resulting in a permanently lowered climate benefit of the forest. Whatever reasons given for shortening the rotation periods relative to today's forestry practice thus must take into account also the resulting negative effects on forests' climate change mitigation potential.

It should be noted that in our simulation study we estimated a climate change mitigation efficiency of 0.72 t CO_2 m^{-3} of utilized wood. This could be considered as a high value (supported by the assumption that harvested wood is used mainly for long-lived construction purposes and bioenergy) when compared to what has been published in other studies in a range between 0.47 and 0.78 t CO_2/m^3 (e.g. Werner *et al.* 2010; Lundmark *et al.* 2014, Braun *et al*. 2016). If we had used a lower climate change mitigation efficiency the positive climate benefit of prolonging rotations would have been somewhat larger but still of a temporary character.

Opposing views on the climate change mitigation effects of forestry and the use of forest-based products are often presented due to different assumptions of the temporal and spatial system boundaries adopted in different analyses (Holtsmark 2012; Lundmark et al. 2014; Nabuurs and Masera 2007; Naudts et al. 2016). In this study we apply a perspective recognizable by forestry practice in Fennoscandia and asses the effects on even-aged forests' climate change mitigation potential by prolonging and shortening the rotation lenghts. We compare our constructed rotation lengths scenarios with a reference scenario set by optimising the NPV of the forest at a discount interest rate of 2%. Since the tree species composition is not altered in the different alternatives possible effects on albedo has not been included in the estimate of climate change mitigation potential.

Our approach is purely deterministic, and the analysis ignores many factors that make stand development and economic revenue everything but deterministic in reality (e.g., disturbances, market fluctuations). When comparing different rotation lengths the time frame for comparison is important. We made the comparison of long term carbon balance in two steps. Firstly, we estimated the carbon balance of altered rotations relative to a reference rotation where NPV was optimal. Secondly, the mean value for annual carbon balance was compared. This value would not change if the time frame was extended to include more rotation cycles if rotation lengths remain unchanged for the alternatives. In contrast, the comparison of the cost for possible climate benefits obtained by deciding altering rotations at the time when final felling was planned for the economically optimal reference scenarios is based on different time frames, which results in a slightly overestimated gain from extending the rotation length. This is because the positive effects of increased carbon stock are temporary, while the substitution effects will be permanently lowered when rotations are prolonged. It also means that if we let the analysis cover many rotation cycles, the gain of increasing the average carbon stock in the forest would eventually be replaced by a reduced climate benefit due to a permanently lower mean annual wood production.

Despite these simplifications we conclude that moderate prolongation of rotation lengths (+10 years) for spruce can give a permanent climate benefit as it increases both forest carbon stocks and yield. In contrast, for pine (all prolonged rotation lenghts scenarios) and for spruce (+20 and +30 years) the climate benefit is only temporary as it is restricted to the first new rotation with the increased rotation length due to that the increased standing forest carbon stock is coupled to a permanently lowered yield. Also for all scenarios increased rotation lengths result in decreased economic return estimated as a decrease in NPV.

Our study supports the idea that average forest growth and yield together with the product use strategy are the main determinators of the long term climate benefit of forestry and are more important than the management practices per se (Lundmark et al. 2016). With this in mind strategies primarily directed to increase average forest growth during a rotation rather than increasing the rotation length would be a more efficient way to improve forests’ potential to mitigate climate change. The relatively high costs for improved carbon balance when extending rotation length also call for new studies focusing on the economical outcome for management practices directed to increase forest growth if also a potential climate benefit was to be included as a additional ecosystem service.

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Table 1. An overview of the assessed different rotation length alternatives. Site index was determined by dominant tree height at the age of 100 years. The high productive sites represented a site index of 30 m for Norway spruce (G30) and 24 m for Scots pine (T24) while corresponding figures for the low productive sites where 18 m (G18) and 16 m (T16).

Species	Site index	Number of thinnings	Reference rotation length (Yr)*	Mean annual increment at reference rotation ($m^3ha^{-1}yr^{-1}$)	Simulated altered rotation lengths (Yr)
Norway spruce	G18	1	110	3.0	100, 110, 120, 130, 140
Norway spruce	G30	2	75	10.0	65, 75, 85, 95, 105
Scots pine	T16	1	110	3.2	100, 110, 120, 130, 140
Scots pine	T24	1	85	6.1	75, 85, 95, 105, 115

*The reference rotation length for spruce and pine at the high and low productive sites was defined by optimizing net present value using an interest rate of 2%.

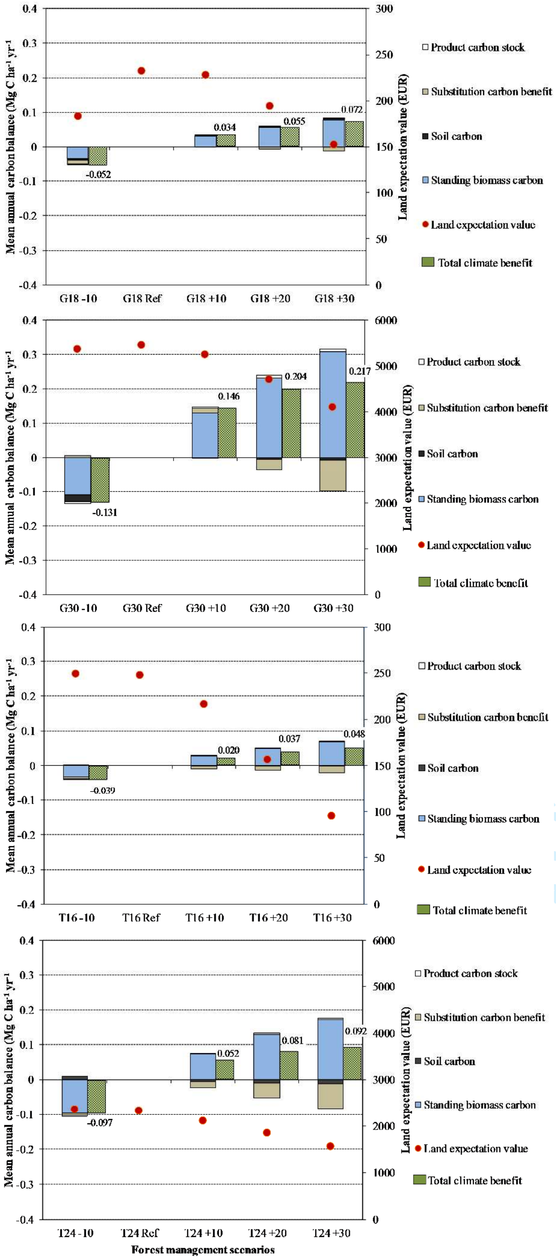

Figure 1. Mean annual carbon balance (Mg C ha^{-1} year^{-1}) (left axis) and Land Expectation Value (EUR) (right axis) for the different rotation lengths in relation to the reference rotation length for the two most common tree species in Fennoscandia, Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), growing on high and low productive sites. Site index was determined by dominant tree height at the age of 100 years was used to describe the fertility of the sites. The high productive sites represented a site index of 30 m for Norway spruce (G30) and 24 m for Scots pine (T24) while corresponding figures for the low productive sites where 18 m (G18) and 16 m (T16). Colored bars show the different components of the carbon balance and the green spotted bar the sum of all components (=total climate benefit). Negative values denote lower climate benefits than the reference

rotation length. Land expectation value for each rotation length was based on an interest rate of 2% and a current timber price-list and operations cost statistics from the Swedish forestry industry, and are presented as colored dots.

Table 2. Calculated costs (€ per Mg of carbon) for the marginal effect on the improved carbon balance by prolonging the rotation length with +10, +20 or +30 years for Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), growing on high and low productive sites. Site index was determined by dominant tree height at the age of 100 years was used to describe the fertility of the sites. The high productive sites represented a site index of 30 m for Norway spruce (G30) and 24 m for Scots pine (T24) while corresponding figures for the low productive sites where 18 m (G18) and 16 m (T16). Costs were expressed as the reduction in Net Present Value (NPV) relative to the reference rotation for each prolonged rotation alternative divided by the total climate benefit of the corresponding prolonged rotation relative to the climate benefit of the reference scenario. NPV included the net revenue from final felling and the LEV for coming tree generations, assuming that the coming generations would continue to be managed with the prolonged rotation length.

Rotation length	Cost in NPV (€ ha^{-1}) relative to the reference rotation	Accumulated climate benefit (Mg C ha^{-1}) by prolonging the rotation length relative to the reference rotation	Cost per Mg of carbon in improved carbon balance (€ Mg^{-1} C)
G18/+10	37	4.0	9
G18/+20	339	7.2	47
G18/+30	713	10.1	71
G30//+10	946	12.4	76
G30/+20	3389	19.4	175
G30/+30	6077	22.8	266
T16/+10	285	2.4	120
T16/+20	813	4.8	168
T16/+30	1363	6.8	202
T24/+10	1162	5.0	235
T24/+20	2624	8.5	308
T24/+30	4199	10.6	396