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Environmental Science & Policy 7 (2004) 205–219

Environmental Science & Policy

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Managing carbon sinks by changing rotation length in European forests

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Abstract

Elongation of rotation length is a forest management activity countries may choose to apply under Article 3.4 of the Kyoto Protocol to help them meet their commitments for reduction of greenhouse gas emissions. We used the CO2FIX model to analyze how the carbon stocks of trees, soil and wood products depend on rotation length in different European forests. Results predicted that the carbon stock of trees increased in each forest when rotation length was increased, but the carbon stock of soil decreased slightly in German and Finnish Scots pine forests; the carbon stock of wood products also decreased slightly in cases other than the Sitka spruce forest in UK. To estimate the efficiency of increasing rotation length as an Article 3.4 activity, we looked at changes in the carbon stock of trees resulting from a 20-year increase in current rotation lengths. To achieve the largest eligible carbon sink mentioned in Article 3.4 of the Kyoto Protocol, the rotation lengths need to be increased on areas varying from 0.3 to 5.1 Mha depending on the forest. This would in some forests cause 1–6% declines in harvesting possibilities. The possible decreases in the carbon stock of soil indicate that reporting the changes in the carbon stocks of forests under Article 3.4 may require measuring soil carbon.

Keywords: Rotation length; Carbon sink; Forest management; Kyoto Protocol; CO2FIX

1. Introduction

The choice of rotation length (time from the establishment of a forest stand to its final felling) is considered to be an effective forest management activity for controlling the carbon stocks of forests (Cooper, 1983; Liski et al., 2001; Pussinen et al., 2002; Harmon and Marks, 2002). It affects the carbon stocks of both trees and soil and, through the effects on the quantity and the quality of harvested timber, also the carbon stock of wood products. A change in rotation length is also seen as a forest management activity that countries may choose to apply under Article 3.4 of the Kyoto Protocol to help them meet their commitments for reduction of greenhouse gas emissions (UNFCCC, 1997, 2001a; IPCC, 2000).

The carbon stock of trees increases with increasing rotation length but the carbon stocks of soil and wood products do not necessarily (Liski et al., 2001). The decreases in the carbon stocks of soil and wood products would make the practice of increasing rotation length less efficient in sequestering carbon. Any decrease in the soil carbon stock would, in addition, make it necessary to measure changes in the carbon stocks of forests for Article 3.4 the Kyoto Protocol. A country may decide not to account for one or more of the five carbon stocks named, i.e. aboveground biomass, belowground biomass, litter, dead wood, and soil organic matter, only if it can show that the stock is not decreasing (UNFCCC, 2001a). Many countries may wish not to account for changes in soil carbon, because they are expensive and difficult to measure. Model simulations of different forests would help to explore the effects of rotation length on the carbon stocks of forests.

Estimates of the rotation length effects on the carbon stocks of forests are scarce, especially those that account for the dynamics between the different stocks of forest carbon and are comparable between different forests. This lack of knowledge is illustrated, for instance, in the estimates given in the special report of the Intergovernmental Panel of Climate Change on Land Use, Land-Use Change and Forestry (IPCC, 2000). The figures given there account only for biomass and are based on a simple assumption that a 15% increase in rotation length increases biomass by 5%. To evaluate the implications of changing rotation length for forest carbon, more thorough analyses are needed.

We studied the efficiency of changing rotation length in managing the carbon stocks of different forests in Europe.

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doi:10.1016/j.envsci.2004.03.001

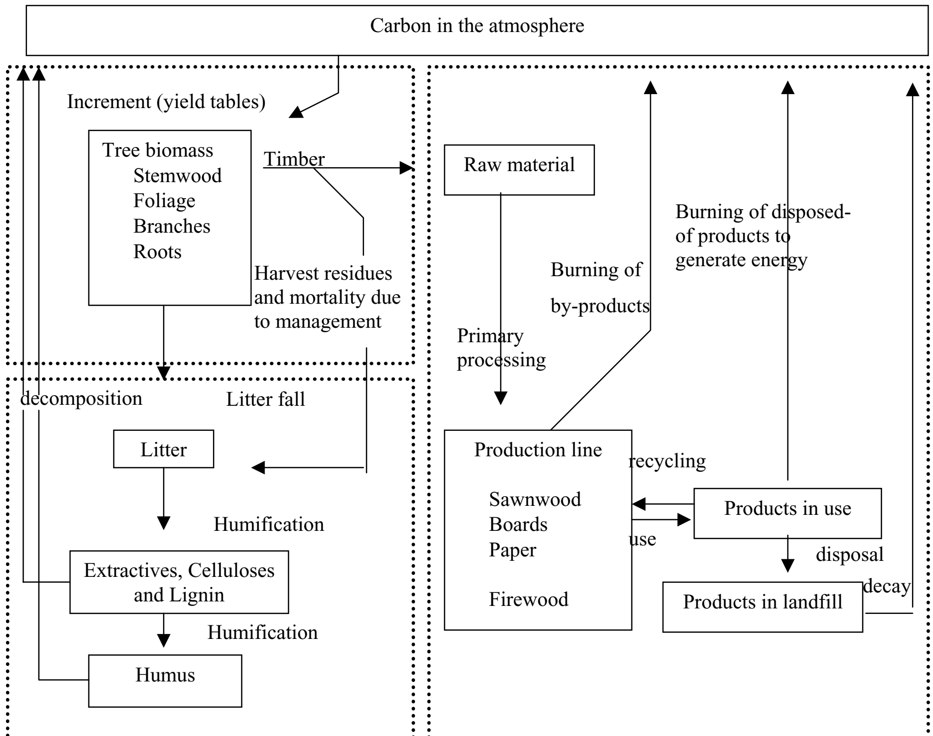


Fig. 1. Structure of the CO2FIX V 2.0 model (Nabuurs et al., 2002). Boxes marked by broken lines represent the three modules of the model: biomass module, soil module and wood products module.

Our specific objectives were (1) to quantify the effects of rotation length on the carbon stocks of trees, soil and wood products and (2) to estimate the size of forest areas where rotation lengths need to be changed to accomplish the largest carbon sink eligible under Article 3.4 of the Kyoto Protocol.[2] We also estimated the effects of the changed rotation lengths on harvest possibilities and considered the implications of the results for the reporting requirements of the sinks under the Kyoto Protocol.

2. Material and methods

2.1. Approach

CO2FIX V 2.0 model was applied to analyse the effects of rotation length in this study (Nabuurs et al., 2002; Masera et al., 2003). CO2FIX is a stand-level bookkeeping model that simulates the stocks and the fluxes of carbon in forests and wood products (Fig. 1). The model consists of a tree module, a soil module and a wood product module, and it operates on an annual time step. We used CO2FIX to calculate average carbon stocks over different rotation lengths. These averages represent steady-state carbon stocks in a landscape where each age class of forest covers an equal area (normal forest). Differences between the steady-state carbon stocks represent changes in the carbon stocks if the rotation length was altered. While changing to a new steady state, the forest would act either as a carbon sink or a carbon source.

To estimate the effects of changing rotation length from the currently used, we studied differences in the average carbon stocks between the currently recommended and 20-year longer rotation lengths. The annual carbon sinks or sources were estimated by dividing the total difference by 20 years, which is theoretically the shortest time required to reach the new age-class distribution with the increased rotation length. To evaluate the efficiency of increasing rotation length with regard to Article 3.4 of the Kyoto Protocol, we accounted for tree carbon only and estimated the area where rotation length need to be changed to reach the maximum eligible sink in the countries studied (UNFCCC, 2001b).

2.2. Simulations

2.2.1. Countries and tree species

Four countries were chosen to represent the different climatic conditions of Europe: Finland representing the Northern Europe, Germany representing Central Europe, UK representing Atlantic Europe and Spain representing Southern Europe. In these countries, we studied tree species having economic importance: Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) forests were simulated in Finland and Germany, Sitka spruce (*Picea sitchensis*) forests in UK,

[2] The largest sinks eligible under Article 3.4 of the Kyoto Protocol were determined by country in the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change in Bonn 2001, and for the countries of this study, these values are given in Table 3.

Table 1
Main characteristics of the studied forests

	FI Scots pine	FI Norway spruce	DE Scots pine	DE Norway spruce	GB Sitka spruce	ES Scots pine	ES Maritime pine
Currently recommended rotation length (years)	90	90	120	100	40	100	80
Mean annual temperature (°C)	3.4	3.4	9.7	9.7	9	14.2	14.2
Summer drought (mm)	7.1	7.1	−98.1	−98.1	−8	−409.6	−409.6
CAI ($m^3\,ha^{-1}$ per year)							
Age							
20	7.3	3.1		2.4	14.8		
30	8.5	7.9	9.4	9.8	20.6		7.6
40	9.4	10.3	9.1	14.4	20.7	9	7.8
50	9.2	10.6	8.5	14.8	17.1	9.7	8.2
60	8.4	10.6	7.5	13.6	12.8	10.4	8.3
70	7.0	9.4	6.9	12.2	9.9	10	8.1
80	5.7	8.6	6.5	10.8	7	9.6	7.6
90	4.9	8.0	6	10		8.3	7.2
100	4.6	7.5	5.4	9.4		7.6	6.7
110	4.3	7.2	4.9	8.4		7	6.1
120		7.0	4.4	8		6	5.6
130			3.9				
140			3.5				

FI: Finland, DE: Germany, GB: UK, ES: Spain, summer drought: precipitation of the growing season—potential evapotranspiration of growing season (mm), CAI: current annual increment ($m^3\,ha^{-1}$ per year).

and Scots pine and Maritime pine (*Pinus pinaster*) forests in Spain (Table 1). CO2FIX was parameterised for the simulations as advised in the manual of the model (Nabuurs et al., 2002; Masera et al., 2003), and single cohort, even-aged forests were simulated.

2.2.2. Biomass parameters

Current annual increment (CAI) was taken from local growth and yield tables (Table 1) (Koivisto, 1959; Wiedemann, 1949; Hamilton and Christie, 1971; Garcia Abejon and Gomez Loranca, 1984, 1989). CO2FIX converts the values of stemwood volume to biomass and carbon using wood density and carbon content coefficients. We derived the wood densities (Appendix A) from the CO2FIX manual (Nabuurs et al., 2002) and assumed 50% carbon content for all biomass. To calculate other biomass compartments, i.e. foliage, branches and roots (fine roots are excluded at CO2FIX), the model needs their growth rates relative to the growth of the stem. We determined these relative growth rates by first calculating the biomass of each compartment using biomass equations (Marklund, 1988; Ter-Mikaelian and Korzukhin, 1997; Gracia et al., in press) and yield tables, and then calculating the periodic growth and comparing that to the periodic growth of the stem. The model calculates the litter production of the biomass compartments by multiplying the biomass values by turnover coefficients. We derived these turnover coefficients (Appendix A) for foliage from Kellomäki et al. (1992) and for branches and roots from Liski et al. (2002).

Thinning regimes (Appendix A) were taken from national guidelines for forest management or, if these were not available, they were derived from yield tables (Metsätalouden Kehittämiskeskus Tapio, 2001; Wiedemann, 1949; Canellas et al., 2000; Falcão, 1998). The timing and the quantity of the thinnings had only a small effect on the carbon stocks if they varied within reasonable limits (10% more or less intensive thinnings than the one chosen, thinnings made 5–10 years earlier or later). This was found out by simulating the different thinning regimes for 90-year rotation of Scots pine forests in Finland.

To analyse the effect of rotation length, we simulated rotation periods at 10-year intervals and at the end of each rotation the stand was clear-felled. Branches, foliage, roots and 10–15% of stemwood from the thinnings and the final cuttings were transferred to litter, whereas the rest of stemwood was transferred to wood products (Appendix A).

2.2.3. Soil parameters

General parameters for coniferous forests were used in the soil module (Nabuurs et al., 2002; Karjalainen et al., 2002). Climate data (annual mean temperature (°C) precipitation during the growing season (mm) and potential evapotranspiration during the growing season (mm) Table 1) that determine the decomposition rates of soil carbon in the model were derived from a global dataset (http://www.worldclimate.com). Initial soil carbon stocks were calculated and added to the soil module on the basis of preparatory simulations, which were done to determine the mean annual carbon input to forest soil with each rotation length.

2.2.4. Wood product parameters

Harvested wood was divided into logwood, pulpwood and harvest residues. We assumed that there was no logwood

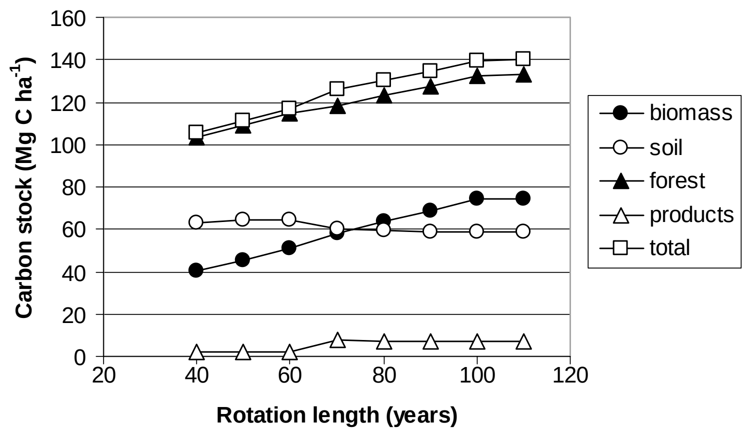


Fig. 2. Mean carbon stocks over the rotation of Scots pine forests in Finland when using different rotation lengths. Biomass includes the living biomass of trees (excl. fine roots), soil includes litter and soil organic matter, forest includes biomass and soil, products means wood products in use and total is the sum of biomass, soil and products.

until the mean diameter of trees in the stand exceeded 20 cm according to the yield table used. Before this, 85% of the harvested wood was pulpwood and the rest was harvest residues. When the mean diameter exceeded 20 cm, 30% of the harvested roundwood was allocated to logwood, 60% to pulpwood, and the rest to soil as harvest residues in thinnings; in final fellings, 60% was allocated to logwood and 30% to pulpwood. In the product module of the CO2FIX model, the harvested wood was then allocated into four product categories (Fig. 1, Appendix B). Production losses were reallocated to other product categories and products were assumed to have a certain life span after which they were recycled, used for bioenergy or disposed into landfill (Appendix C). The parameters of the product module were defined separately for each country and tree species by slightly modifying the values given in Karjalainen et al. (1994). Because of the large uncertainties related to landfills, they were excluded from our study.

3. Results

3.1. Scots pine forests in Finland

To demonstrate the mechanisms that determine the effects of rotation length on the carbon stocks of forests, we explain the Finnish Scots pine case in detail.

The average carbon stock of trees was the larger the longer was the rotation length (Fig. 2). This was because the annually harvested forest area decreased with increasing rotation length. For example, the average carbon stock of trees was 17 Mg ha^{-1} or 29% larger when a 110-year rotation length was applied instead of a 70-year length that maximised timber production. The carbon stocks of soil and wood products followed the pattern of net primary productivity (NPP), i.e. the carbon flux to the system. In the Finnish Scots pine forests, NPP was highest when a 60-year rotation length was applied but it decreased only slightly when the rotation

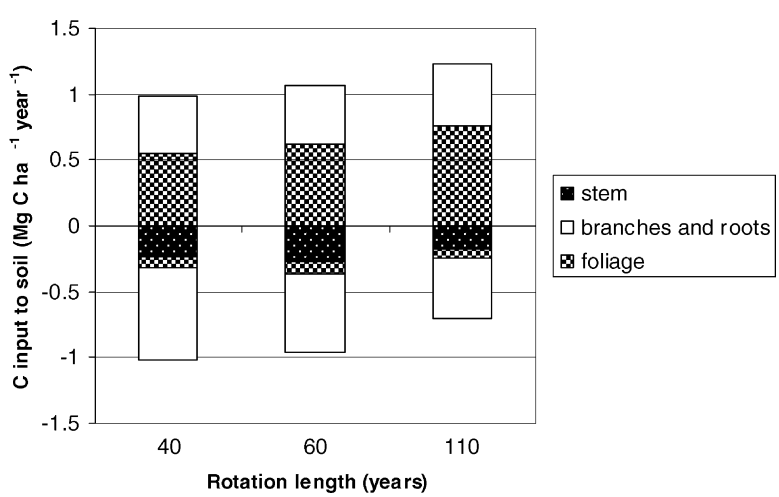


Fig. 3. Mean annual carbon input to the soil of Scots pine forests in Finland by biomass compartment when using different rotation lengths. Above the *x*-axis are litter production of living trees and natural mortality of trees and below the axis are harvest residues.

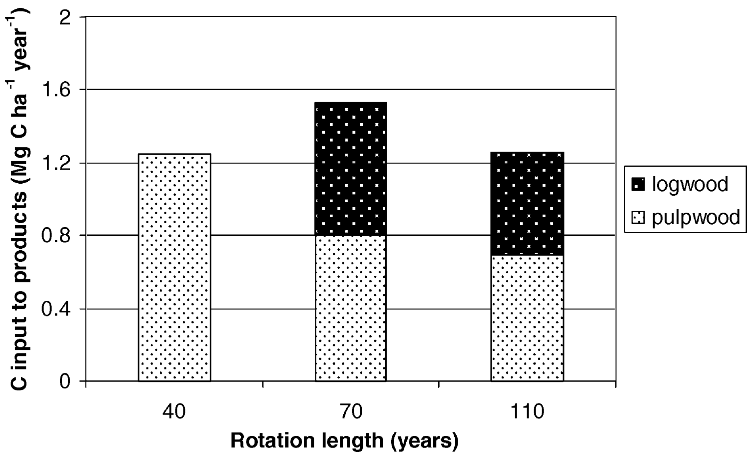


Fig. 4. Mean annual harvests of Scots pine forests in Finland when using different rotation lengths.

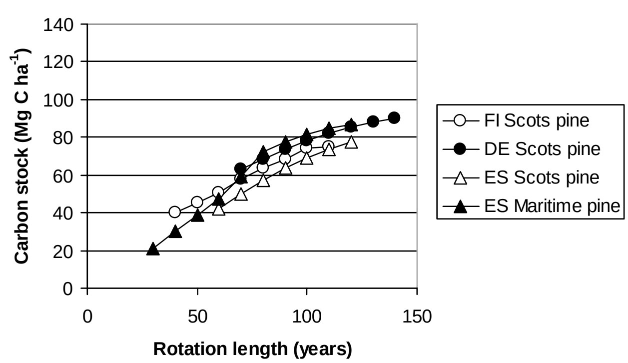
length was changed. As a result of this small effect of rotation length on the carbon flux to the system, the carbon stock of the soil was less sensitive to rotation length than the carbon stock of trees was. The average carbon stock of soil was only 6 Mg ha^{-1} (9%) smaller when the rotation length was increased from 60 to 110 years. When such a long rotation length was applied, the large tree biomass produced a lot of litter but there were less harvest residues because of the decreased harvests and because the larger trees harvested left less harvest residues per harvested volume (Fig. 3).

The carbon stock of wood products was dependent on both the quantity and the quality of harvested timber. The stock was largest when a 70-year rotation length was applied (Fig. 4). When the rotation length was shorter, the volume of harvests decreased and the timber harvested had smaller dimensions meeting only the requirements for pulpwood; such timber could only be used for short-lived products. Increasing the rotation length from 70 years decreased the harvests but the average carbon stock of wood products did not decrease very much; this was because the mean age was higher and the life span of the products manufactured from the larger-sized timber increased simultaneously. When a 110-year rotation length was applied instead of 70 years, the average carbon stock of wood products was decreased by 1.1 Mg ha^{-1} (14%).

The total amount of carbon in the forest (trees + soil) and in the whole system (trees + soil + wood products) increased with increasing rotation length, following the trends in the carbon stock of trees (Fig. 2).

3.2. Different European forests

Rotation length had a larger effect on the carbon stock of trees in the spruce than in the pine forests (Fig. 5). This was because the growth of trees was more age-dependent in the spruce than in the pine forests. The average carbon stocks of soil and wood products varied according to the carbon flux into the system (Figs. 6 and 7). The carbon stock of soil was affected least by rotation length in the Scots pine forests in Finland and Germany, where it, quite surprisingly, decreased slightly with increasing rotation length (Fig. 6). For both kinds of pine forests in Spain, the result was different because of a different biomass allocation. Old trees had still a lot of other than stem biomass, and, consequently, the calculated values of NPP (Fig. 8) and litter production remained high and the carbon stock of soil increased with increasing rotation length. In all spruce forests analysed, NPP and the average carbon stock of soil increased with increasing rotation length until 80 or 90 years but not anymore with a further increase in rotation length. The total carbon



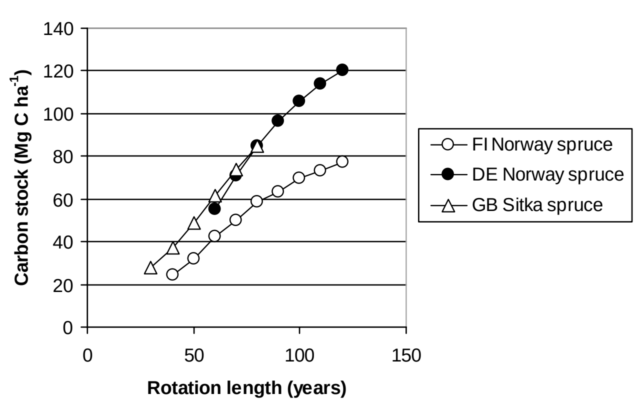


Fig. 5. Carbon stock of trees in forests in Finland (FI), Germany (DE), Spain (ES) and the UK (GB) when using different rotation lengths.

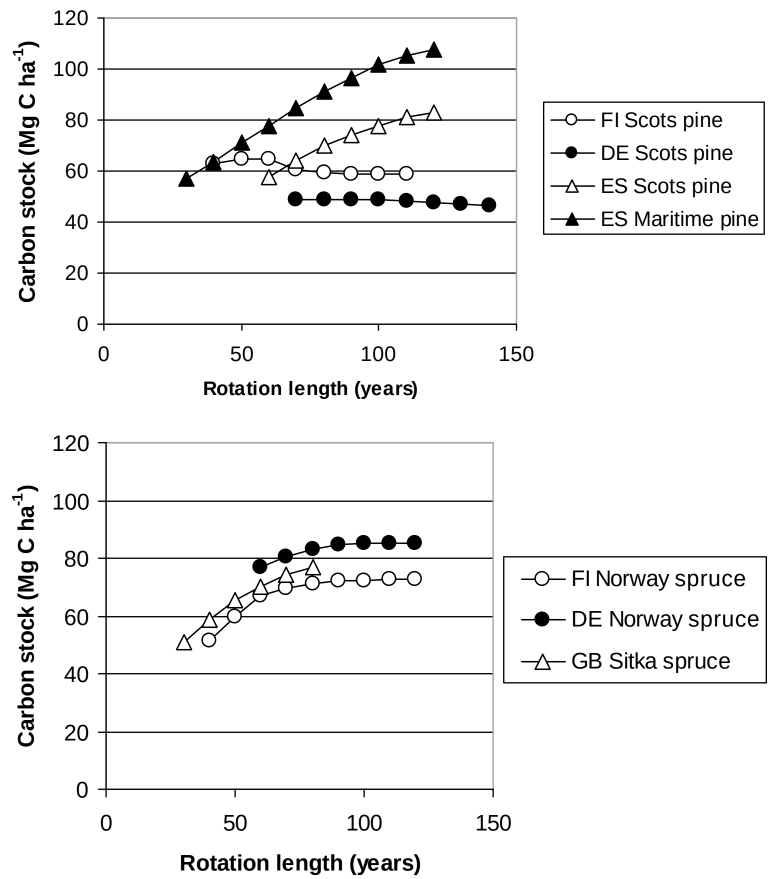


Fig. 6. Carbon stock of soil in forests in Finland (FI), Germany (DE), Spain (ES) and the UK (GB) when using different rotation lengths.

stock in forest (trees + soil) increased with increasing rotation length in each forest following the trend in the carbon stock of trees. In the Scots pine forests in Finland and Germany, the total carbon stock in forest (trees + soil) increased slightly less than the carbon stock of trees, because of the decrease in the carbon stock of soil. The average carbon stock of wood products increased with increasing rotation length until 70–100 years, depending on the forest, and decreased slightly with any further increase in rotation length (Fig. 7). In the Scots pine forests in Finland and in the Norway spruce forests in both Finland and Germany, the average carbon stock of wood products was substantially increased when the rotation length was extended above 60 years. At this age in these forests, part of the harvested wood was already logwood, which increased the life span of the products (see Appendix C).

The trends in the carbon stock of wood products did not change the trends in the total carbon stock of the systems (Fig. 9), because the changes were an order of magnitude smaller than those of the carbon stock in the forest.

3.3. Increasing the current rotation lengths by 20 years

The forests studied here differed considerably from each other in terms of the effects of a 20-year increase in the currently recommended rotation lengths. Increasing rotation length by 20 years from that currently recommended had considerably different effects on the various forests studied here. The average carbon stock of trees was estimated to increase least, by 5–8 Mg ha^{-1}, in the Scots pine forests. In the Norway spruce and the Maritime pine forests, it increased two or three times as much, 9–15 Mg ha^{-1}, and, in the Sitka spruce forest, even five times as much, 25 Mg ha^{-1} (Table 2). The average carbon stock of soil was estimated to increase considerably in the Sitka spruce forests in UK and the Maritime pine and the Scots pine forests in Spain (Table 2). In these forests, the carbon stock of soil increased as much as the carbon stock of trees or by half of that amount. In all the other forests, soil carbon changed only slightly. The average carbon stock of wood products was estimated to increase by less than 1 Mg ha^{-1} in all cases, except for the Sitka spruce case in the UK where the estimated increase was 4 Mg ha^{-1} (Table 2).

3.4. Reaching the largest sinks eligible in the Kyoto Protocol

Forest areas on which the currently recommended rotation lengths would need to be increased by 20 years to reach the largest carbon sinks eligible under Article 3.4 of the Kyoto Protocol varied considerably between forests and countries, depending on the effects of the increased rotation length

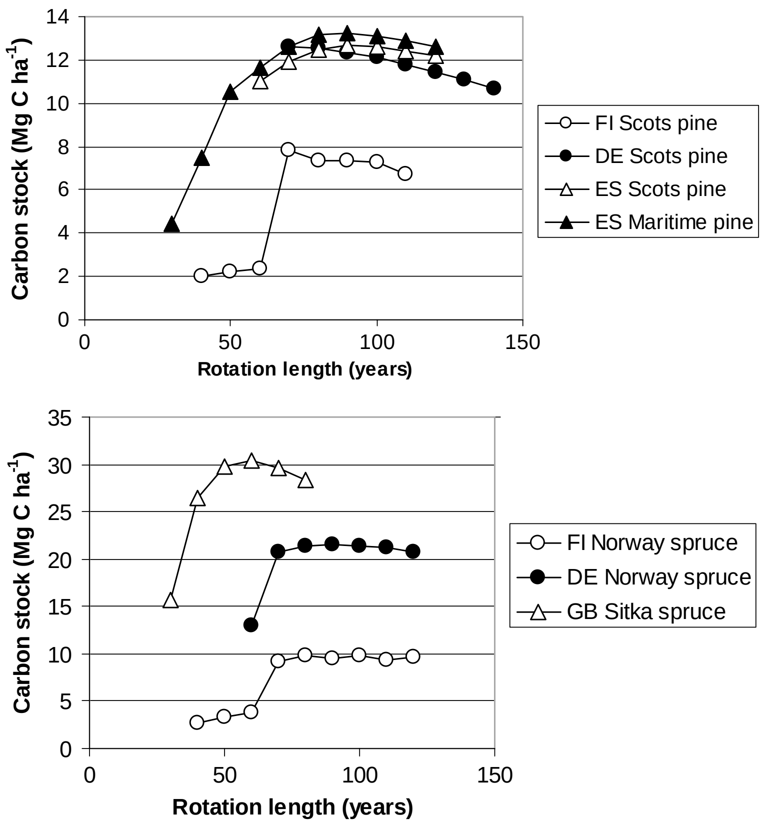


Fig. 7. Carbon stock of wood products of forests in Finland (FI), Germany (DE), Spain (ES) and the UK (GB) when using different rotation lengths.

Table 2
Change in carbon stocks when using 20 years longer rotation length than currently recommended in forests in Finland (FI), Germany (DE), the UK (GB) and Spain (ES)

Forest	Elongation of rotation lengths	Change in carbon stocks (Mg ha^{-1})				
		Trees	Soil	Forest	Products	Total
FI Scots pine	From 90 to 110	6.0	0.1	6.1	−0.6	5.5
FI Norway spruce	From 90 to 110	9.5	0.5	10.2	−0.1	10.0
DE Scots pine	From 120 to 140	4.8	−1.0	3.8	−0.7	3.1
DE Norway spruce	From 100 to 120	14.5	0.1	14.6	−0.6	14.0
GB Sitka spruce	From 40 to 60	24.6	11.7	36.3	4.0	40.3
ES Scots pine	From 100 to 120	8.0	4.9	12.9	−0.4	12.4
ES Maritime pine	From 80 to 100	9.3	10.4	19.7	−0.1	19.6

Table 3
Tree carbon sink resulting from a 20-year increase in the rotation lengths, maximum eligible sinks of Article 3.4. of the Kyoto Protocol, areas needed to accomplish the maximum eligible sink and the effects on harvesting

Forest	Tree C sink (Mg C ha^{-1} per year)	Maximum eligible sink (Tg per year)	Area needed (Mha)	Current area of tree species (Mha)	Area needed/ current area (%)	Change in harvests	
						Percentage	Mm^3 per year
FI Scots pine	0.3	0.16	0.5	12.9	4.1	−5.9	−0.21
FI Norway spruce	0.5	0.16	0.3	4.9	6.9	0.5	0.01
DE Scots pine	0.2	1.24	5.1	2.8	183.2	−5.4	−1.71
DE Norway spruce	0.7	1.24	1.7	3.2	53.3	−1.4	−0.22
GB Sitka spruce	1.2	0.37	0.3	0.7	43.0	13.2	0.47
ES Scots pine	0.4	0.67	1.7	1.5	111.8	−1.1	−0.13
ES Maritime pine	0.5	0.67	1.4	1.5	96.5	2.2	0.2

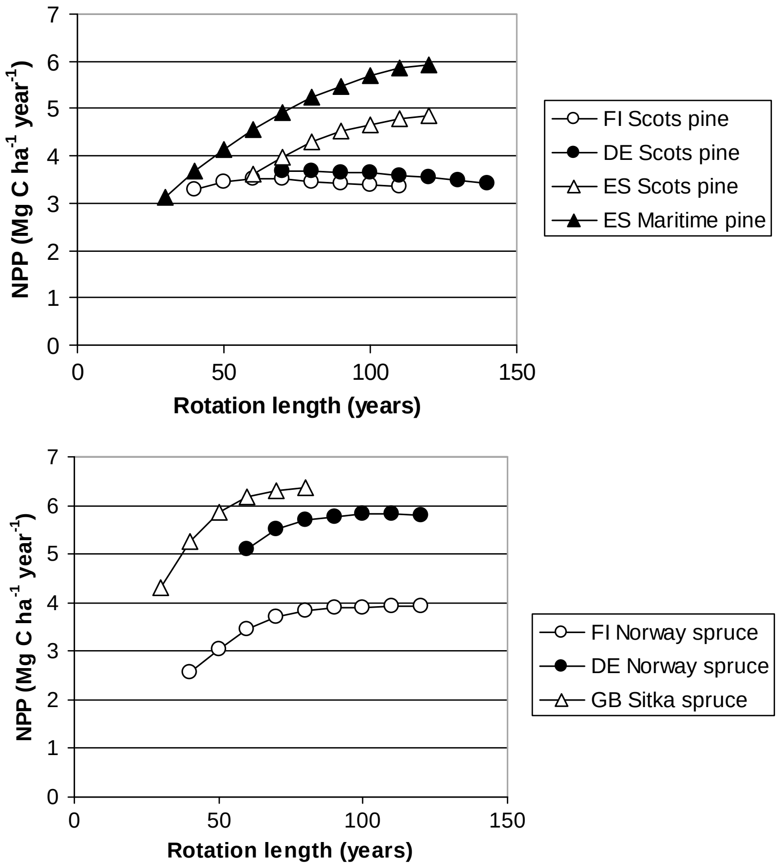


Fig. 8. Net primary production (NPP) in forests in Finland (FI), Germany (DE), Spain (ES) and the UK (GB) when using different rotation lengths.

and the eligible carbon sinks. We limited this analysis to the carbon stock of trees and discuss the implications of this limitation in Section 4.

The required areas were largest, 1.4–5.1 Mha, in Germany and Spain, mainly because of the large eligible sinks in these countries (Table 3). The required areas were smallest for Norway spruce forests in Finland (0.3 Mha) and Sitka spruce forests in the UK (0.3 Mha). The former were mainly a result of the small eligible sink in Finland, the latter from the high sink estimate per hectare.

In Germany and Spain, the estimates of the required areas compared to the current areas covered by these forests, are large or even exceed them. In Finland, on the other hand, the required areas are only a few percent of the current coverage of the analysed tree species. The 20-year increase in rotation length in areas required reaching the largest eligible sink would increase harvests by 13% in the Sitka spruce forests in the UK and change the harvests by only a few percent in all the other forests.

4. Discussion

4.1. Reliability of the results

Reliability of the results of this study depends on, first, how realistically CO2FIX model describes carbon cycling in forests and, second, the parameter values used. We evaluated the overall reliability of our results by comparing them to various measurements.

The growth and yield tables we used were based on a large number of measurements but most of these measurements were old and thus did not account for the recently increased growth rates in European forests (Spiecker et al., 1996). On the other hand, the measurements were often made in fully stocked stands, and the actual forests are rarely fully stocked and may therefore have lower growth rates. This might be the reason why the growth rates used in Finland were around 40% higher than those measured in the National Forest Inventory for the same forest types (Koivisto, 1959; Schelhaas et al., 1999). The growth and yield tables are probably less reliable for old stands, because there are usually less measurements from them. This adds uncertainty to our results for the longest rotation lengths.

Local biomass equations were used in our calculations whenever available; but for the Sitka spruce forests in the UK, we had to apply equations from Alaska (Ter-Mikaelian and Korzukhin, 1997), and for the pine and the spruce forests in Germany, equations from Sweden (Marklund, 1988). In addition, we had to use the Swedish equations for root biomass in all forests. We do not know how the use of these equations affected the results of Sitka spruce in UK or Scots pine in Germany, but Wirth et al. (2004) explored

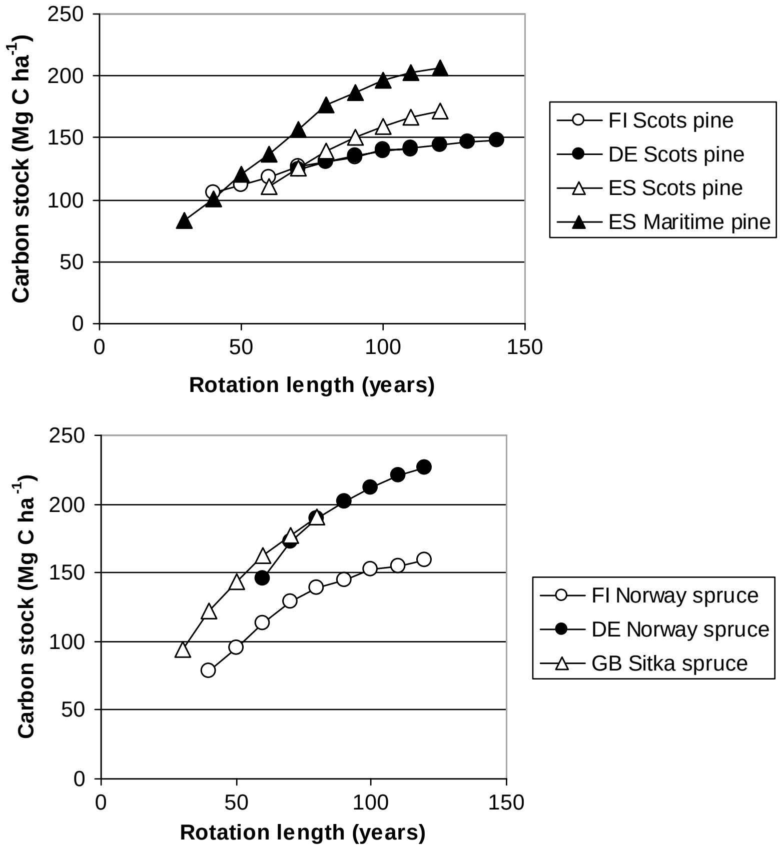


Fig. 9. Compounded carbon stock of trees, soil and wood products of forests in Finland (FI), Germany (DE), Spain (ES) and the UK (GB) when using different rotation lengths.

the performance of Marklund's (1988) equations for predicting biomass of spruce in Central Europe. They found that Marklund's equations accurately predicted stem biomass but slightly underestimated branch biomass and overestimated biomass of needles, dry branches and roots by about 25%. In Spain, the Swedish root equations (Marklund, 1988) probably underestimated the root biomass, but we do not know how our results for the effects of rotation length were affected, because we do not know whether the error was different for young and old trees. Our results are sensitive to the biomass equations applied; and better knowledge of these equations would improve the reliability of the results.

The estimates for soil carbon were found to be comparable to measurements available. In Finland, the average amounts of soil carbon in the kind of pine and spruce forests analysed have been measured to be 60 and 80 Mg C ha^{-1}, respectively (Liski and Westman, 1995); this is very close to the current estimates (see Fig. 6). In Germany, our estimates of soil carbon in pine forests were comparable to the class "very low" (<70 Mg C ha^{-1}) and in spruce forests to the class "low" (70–90 Mg C ha^{-1}) (Baritz et al., 1999). These classes are found in regions of Germany where there are Scots pine and Norway spruce forests. In Finland, coniferous forests have been measured to accumulate soil carbon at an average rate equal to 4.8 g m^{-2} per year with standard deviation of ±1.5, as the stands grow older; this estimate is based on soil carbon measurements at 488 sample plots established by the National Forest Inventory (Peltoniemi, submitted manuscript). Our average simulated value for Scots pine forests in Finland was 6.0 g m^{-2} per year after the local minimum some 30 years after the final felling. For Norway spruce forests in Finland, our estimate was higher, 17 g m^{-2} per year. This is still lower than the value of 30–40 g m^{-2} per year that was calculated from measurements taken along a chronosequence of sites in Norway (Kjønaas, personal communication).

Our results for wood products could not be compared to any measurements, because the calculated stocks were potential stocks per hectare and such measurements were not available. A sensitivity analysis carried out revealed that the simulated overall amount of wood products was quite sensitive to the logwood percentage used for harvested wood but this percentage had little effect on the simulated differences between rotation lengths. Decreasing the logwood percentage by 10% decreased the average carbon stock of wood products by 13% and a similar increase in the percentage increased the stock by 17%.

The estimates of net ecosystem exchange (NEE) we derived from the output of the CO2FIX model agreed with measurements (Valentini et al., 2000; SLU, 2002)

Table 4
Comparison of simulated and measured current annual increment (CAI) and net ecosystem exchange (NEE) (Valentini et al., 2000; SLU, 2002)

Simulated forest	Measured site	Age	CAI, simulated	CAI, measured	NEE, simulated	NEE, measured
FI Scots pine	Hyytiälä, Finland	30	8.5	10	2.7	2.5
FI Norway spruce	Asa, Sweden	38	9.3	10.1	3.0	2.8
DE Scots pine	Winand, The Netherlands	80	8.9	6.3	1.7	2.1
DE Norway spruce	Tharandt, Germany	106	9.2	12	2.0	5.4
GB Sitka spruce	Aberfeldy, UK	18	8.6	14	3.6	5.7
ES Maritime pine	Bordeaux, France	29	7.6	18	2.6	4.3

considering comparable climatic conditions at sites with the same tree species and similar site index (Table 4). If the productivity of the measured site was higher, the measured NEE was also higher—except for the German Norway spruce stand, where the measured and the simulated NEE estimates were different although the growth rates were similar.

These comparisons to various measurements suggest that the overall level of our estimates is similar to the measurements. For a more thorough validation of our results concerning the effects of rotation length, however, more data from stands of different ages, especially from old stands, would have been needed.

4.2. *Effect of rotation length on the carbon stocks of forests*

In all forests studied, the carbon stock of the biomass increased when the rotation length was increased. A 20-year increase in current rotation lengths increased the average carbon stock of biomass in studied pine forests by 4.8–9.3 Mg C ha^{-1} or 6–13% and in spruce forests by 9.5–24.6 Mg C ha^{-1} or 14–67%.

The amount of soil carbon decreased in two forests out of seven when rotation length was increased despite an increase in the amount of biomass. This decrease resulted from a decrease in NPP and through that, from a decrease in litter production in old forests. In old forests, NPP may decrease because of increased respiration burden due to increasing woody biomass, decreased leaf area and light interception, decreased nutrient availability, decreased photosynthesis due to decreased hydraulic conductivity in old trees, or a shift in carbon allocation from above- to below-ground production (Smith and Resh, 1999). Although the amount of soil carbon did not decrease much, and the effect on the total forest carbon was small, it may be of importance for the reporting requirements of Article 3.4 of the Kyoto Protocol—strict interpretation of the Protocol means that if a country cannot prove that the accountable pool is not a source, it must be measured (UNFCCC, 2001a). In the Spanish pine forests, on the other hand, soil carbon increased so much that it enhanced the carbon sink of these forests substantially. Soil carbon increased because much of the growth was allocated to foliage and branches also in old forests, and litter production remained high. In the Sitka spruce forests in the UK, soil carbon also increased considerably when the rotation length was increased, but in these forests the current rotation length was so short that the production of the forests remained high even after the rotation length was increased. In these forests where the soil carbon increased substantially, the countries might be interested also to account for the change of soil carbon under the Kyoto Protocol.

Accounting for the carbon stock of biomass only, accomplishing the maximum eligible sinks of Article 3.4 would mean elongation of rotation length in areas varying from 0.3 to 5.1 Mha depending on the forest and country. The differences between forests resulted from the size of the sink obtained by increasing the rotation length, but also from the maximum carbon sinks allowed to countries under Article 3.4. In all the countries other than Finland, the area needed compared to current area of the species was substantial, and in two cases, Scots pine forests in Germany and in Spain, there would not be enough forest area with that species to achieve the maximum sink. But when the area needed is compared with the total forest area within the country, there would be enough forests also in Germany and Spain to achieve the sink. If we would also take the soil carbon into account, the areas needed to reach the maximum eligible sinks would reduce in the cases where soil carbon increased, and in other cases the decrease in soil carbon was so small that it would only have a minor effect on the areas needed.

The landscapes that we studied were theoretical, and real landscapes have probably not developed with the uniform age-class structure presented in our results. This means that transition from one steady state to a new one with elongated rotation length would probably take more than the 20 years we assumed, mean annual sink would be smaller than what we estimated and due to that, the forest areas needed to achieve the maximum eligible sink would be larger. To gain more realistic estimates about the efficiency of elongating the rotation length, the simulations should be based on the current forest structure.

Our estimates about the potential carbon sinks resulting from the elongated rotation length are 10–50 times larger than the estimates by the IPCC (2000), which estimated the carbon sinks resulting from the increased rotation length to be 0.022–0.036 Mg C ha^{-1} per year in Canada, USA and The Netherlands. One reason for our larger estimates is that we assumed the effect for 20 years whereas IPCC assumed it for 80 years. But even if we took that into account, our results remain two to ten times larger, meaning that elongation of rotation length would be more efficient in managing carbon sinks than had been thought previously.

Elongation of rotation length would also affect the harvesting possibilities. In three of the forests studied, these possibilities increased by 0.5–13% when the rotation length was elongated by 20 years from the currently recommended length; and in four forests, they decreased by 1–6%. For comparison, in the 1980s harvests in the whole of Europe increased by 4.5%. The decrease of harvesting possibilities can be seen as the price of the carbon sink resulting from the elongated rotation lengths. The longer rotation length would also decrease the amount of harvest residues that could be used to produce bioenergy. Substitution of fossil fuels was however not taken into account in this study.

The same increase in the rotation length helped to sequester more carbon in spruce than in pine forests. In addition, harvesting possibilities decreased more in pine forests than in spruce forests, meaning that by increasing the rotation lengths in spruce forests, smaller areas would be needed to achieve the maximum eligible sink of Article 3.4, and harvesting possibilities might even increase a little.

Acknowledgements

This study was partly funded by the European Commission through CASFOR II (ICA4-CT-2001-10100) project. We thank Taru Palosuo and Marcus Lindner for comments and two anonymous reviewers for constructive remarks.

Appendix A

Parameters of biomass module

Case study	Rotation lengths	Thinnings for the longest simulated rotation length, thinning age and fraction removed	Allocation of harvested biomass in fellings harvesting age and fractions allocated to log/pulp/slash
Finland Scots pine	40–110	35/0.35, 50/0.3, 75/0.25, 90/0.25	Thinnings: 35–50(0/0.85/0.15), 75–90(0.3/0.6/0.1) Final fellings: 40–60(0/0.85/0.15), 70–120(0.6/0.3/0.1)
Dry wood density: 0.49 Turnover rate of foliage[a]: 0.25			
Finland Norway spruce	40–120	40/0.35, 60/0.3, 80/0.3, 100/0.3	Thinnings: 40–60(0/0.85/0.15), 80–100(0.3/0.6/0.1) Final fellings: 40–60(0/0.85/0.15), 70–120(0.6/0.3/0.1)
Dry wood density: 0.44 Turnover rate of foliage: 0.16			
Germany Scots pine	70–140	30/0.038, 35/0.063, 40/0.074, 45/0.078, 50/0.079, 55/0.077, 60/0.075, 65/0.071, 70/0.068, 75/0.065, 80/0.062, 85/0.06, 90/0.058, 95/0.057, 100/0.059, 105/0.058, 110/0.060, 115/0.060, 120/0.057, 125/0.057, 130/0.055, 135/0.055	Thinnings: 30–55(0/0.85/0.15), 60–135(0.3/0.6/0.1) Final fellings: 70–140(0.6/0.3/0.1)

Appendix A (*Continued*)

Case study	Rotation lengths	Thinnings for the longest simulated rotation length, thinning age and fraction removed	Allocation of harvested biomass in fellings harvesting age and fractions allocated to log/pulp/slash
Dry wood density: 0.49 Turnover rate of foliage: 0.25			
Germany Norway spruce	60–120	25/0.068, 30/0.081, 35/0.088, 40/0.072, 45/0.063, 50/0.058, 55/0.052, 60/0.049, 65/0.049, 70/0.051, 75/0.056, 80/0.057, 85/0.061, 90/0.061, 95/0.059, 100/0.060, 105/0.061, 110/0.062, 115/0.062	Thinnings: 25–60(0/0.85/0.15), 65–115(0.3/0.6/0.1) Final fellings: 60(0/0.85/0.15), 70–120(0.6/0.3/0.1)
Dry wood density: 0.44 Turnover rate of foliage: 0.16			
UK Sitka spruce	30–80	20/0.37, 25/0.45, 30/0.31, 35/0.23, 40/0.18, 45/0.15, 50/0.12, 55/0.09, 60/0.07, 65/0.06, 70/0.05, 75/0.04	Thinnings: 20–35(0/0.85/0.15), 40–75(0.3/0.6/0.1) Final fellings: 30(0/0.85/0.15), 40–80(0.6/0.3/0.1)
Dry wood density: 0.445 Turnover rate of foliage: 0.16			
Spain Scots pine	60–120	30/0.25, 40/0.25, 50/0.25, 60/0.25, 70/0.25, 80/0.25, 90/0.25, 100/0.25, 110/0.25	Thinnings: 30–40(0/0.85/0.15), 50–110(0.3/0.6/0.1) Final fellings: 60–120(0.6/0.3/0.1)
Dry wood density: 0.490 Turnover rate of foliage: 0.25			
Spain Maritime pine	30–120	15/0.15, 20/0.15, 25/0.15, 30/0.15, 35/0.15, 40/0.15, 45/0.15, 50/0.15, 80/0.2, 90/0.2, 100/0.2, 110/0.2	Thinnings: 15–35(0/0.85/0.15), 40–110(0.3/0.6/0.1) Final fellings: 30(0/0.85/0.15), 40(0.3/0.6/0.1), 50–120(0.6/0.3/0.1)
Dry wood density: 0.55 Turnover rate of foliage: 0.25			

[a] Turnover rate of branches and roots was 0.027 in all simulations.

Appendix B

Case-specific parameters of the product module

Case study	Raw material allocation logwood	Raw material allocation pulpwood	Production losses (production line)	Fraction reallocated to		
				Boards	Paper	Firewood
FI Scots pine	Sawnwood: 0.68	Boards: 0	Sawnwood	0	0.44	0.12
	Boards: 0	Paper: 1	Boards		0	0
	Paper: 0.32	Firewood: 0	Paper			0.53
FI Norway spruce	Sawnwood: 0.79	Boards: 0	Sawnwood	0	0.44	0.12
	Boards: 0	Paper: 1	Boards		0	0
	Paper: 0.21	Firewood: 0	Paper			0.07
DE Scots pine	Sawnwood: 0.6	Boards: 0.4	Sawnwood	0.15	0.14	0.1
	Boards: 0.1	Paper: 0.6	Boards		0.1	0.23
	Paper: 0.3	Firewood: 0	Paper			0.5
DE Norway spruce	Sawnwood: 0.6	Boards: 0.5	Sawnwood	0.15	0.14	0.1
	Boards: 0.2	Paper: 0.5	Boards		0.1	0.23
	Paper: 0.2	Firewood: 0	Paper			0.07
GB Sitka spruce	Sawnwood: 0.6	Boards: 0.5	Sawnwood	0.15	0.14	0.1
	Boards: 0.2	Paper: 0.5	Boards		0.1	0.23
	Paper: 0.2	Firewood: 0	Paper			0.07
ES Scots pine	Sawnwood: 0.6	Boards: 0.3	Sawnwood	0.27	0.13	0.17
	Boards: 0.1	Paper: 0.6	Boards		0.08	0.23
	Paper: 0.3	Firewood: 0.1	Paper			0.53
ES Maritime pine	Sawnwood: 0.6	Boards: 0.3	Sawnwood	0.27	0.13	0.17
	Boards: 0.1	Paper: 0.6	Boards		0.08	0.23
	Paper: 0.3	Firewood: 0.1	Paper			0.53

Appendix C

General parameters of the product module

Products allocation (production line)	Fraction allocated to		
	Long term	Medium term	Short term
Sawnwood	0.35	0.45	0.2
Boards	0.2	0.5	0.3
Paper	0	0	1
End of life (product type)	Fraction disposed to		
	Recycling	Energy	Landfill
Long term	0.3	0.35	0.35
Medium term	0.25	0.25	0.5
Short term	0.7	0.15	0.15

Appendix C (*Continued*)

Recycling (product type)	Fraction recycled as		
	Long term	Medium term	Short term
Long term	0	0.5	0.5
Medium term		0	1
Short term			0
Life span			
Long term products (year)	50		
Medium term products (year)	15		
Short term products (year)	1		
Mill site dump (year)	10		
Landfill (year)	100		

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