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Use of wood fuels from boreal forests will create a biofuel carbon debt with a long payback time

Abstract:
Owing to the extensive critique of food-crop-based biofuels, attention and hopes have turned toward second-generation wood-based biofuels. An important question is therefore whether wood from boreal forests could serve as a source for biofuels. However, in a typical boreal forest, it takes 70–120 years before a stand of trees is mature. If this time lag and the real dynamics of the carbon stock of boreal forests more generally are taken into account, it becomes necessary to reconsider the potential mitigation effects of the increased use of wood fuels from boreal forests. This paper finds that the increased harvest of a boreal forest creates a biofuel carbon debt that takes 150–230 years to repay.

Keywords: forestry, greenhouse gas emissions, bioenergy, carbon neutrality

JEL classification: Q23, Q42, Q54, Q58

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1. Introduction

Carbon neutrality of bioenergy combustion is incorporated into most countries' climate policies. No country imposes taxes on CO_2 emissions from the combustion of bioenergy. Moreover, the European Union emissions trading scheme incorporates the assumption that bioenergy is a carbon-neutral fuel; firms included in this market are not supposed to acquire and surrender allowances for emissions from the combustion of bioenergy.

The reasoning behind the carbon neutrality assumption is that the harvest of one crop is replaced by the growth of a new crop, which reabsorbs the quantity of carbon that was released by burning the first crop. This is a reasonable argument in the case of food-crop-based biofuels, as new crops replace those that are harvested usually within one year. However, the carbon neutrality of food-crop-based biofuels has recently been questioned. Fargione et al. (2008) found that converting native habitats to cropland releases CO_2 from both existing vegetation and carbon stored in soils. Fargione et al. (2008) therefore concluded that production of food-crop-based biofuels may create a biofuel carbon debt by releasing CO_2 at a level that is many times more than the level of annual greenhouse gas reductions that these biofuels would provide by displacing fossil fuels.

Searchinger et al. (2008) analyzed the global effects of using grain or existing cropland for biofuel production. They argued that most previous analyses failed to take account of the carbon emissions that occur as farmers worldwide respond to higher crop prices and convert forest and grassland to new cropland to replace the grain or cropland diverted to biofuels (see also Gibbs et al. (2010), Gurgel et al. (2007), Lapola et al. (2010), and Melillo et al. (2009).

More generally, Wise et al. (2009) and Searchinger et al. (2009) underlined that the current practice of accounting CO_2 emissions from combustion of bioenergy as zero means there are strong incentives to clear land, thus releasing large amounts of greenhouse gases.

The criticism of food-crop-based biofuels has not been directed toward wood-based biofuels to the same degree.[1] The world's forests represent potentially large sources of bioenergy. However, because increasing the harvest in tropical forests is not an option for a number of well-known reasons, attention has been drawn toward boreal forests as a potential source for an increased supply of biofuels.

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[1] Goksøyr (2007) represents an important exception.

Especially, the possibility of producing liquid biofuels from wood (second-generation biofuels) is considered a promising alternative to using food crops.

This paper therefore analyzes the mitigation effects of wood fuels from boreal forests. It would be reasonable to argue that wood fuels are carbon neutral if new trees grew so fast that they replaced those that are felled a year later or at least after only a few years. However, this is not the case in a boreal forest. Even after 10 or 20 years, new trees are still only saplings. In typical boreal-forested areas, it takes usually 70–120 years before a stand of trees is mature. This long growth period is in itself an argument for reconsidering the assumption that using timber as fuel is climate neutral. As discussed in the next section, there are other arguments for this conclusion, especially that a permanently higher level of harvest entails a permanently lower stock of carbon stored in the forest.

In this paper, I use numerical examples to illustrate the consequences of replacing the simple assumption that wood is carbon neutral with assumptions that are more realistic about the dynamics of a boreal forest. These numerical examples indicate that increasing the harvest in a boreal forest to replace fossil fuels, including coal, with wood as an energy source may increase CO_2 emissions throughout the 21st century, resulting in a carbon debt with a payback time of 150–230 years. In the case where wood is used as the basis for the production of second-generation liquid biofuels, there is an especially large carbon debt and long payback time.

The numerical examples in this paper are based on the properties of a Norwegian forest. However, the conclusions are relevant to boreal forests more generally. They are not as relevant to forests in warmer climates, which have considerably faster regrowth.

It should also be mentioned that this paper analyzes the consequences of harvesting timber for the sole purpose of increasing the supply of bioenergy. Using by-products from the forest industry as bioenergy is a different and less controversial matter not discussed in this paper.

The next section presents the assumptions and describes the stylized forest model. Section 3 considers the relationship between the harvested volume and the forest's carbon stock in long-term steady states. Section 4 describes the consequences in both the short and long terms of increasing the annual harvested volume. Section 5 studies the net effects on CO_2 emissions when the increased harvest considered in section 4 is used as bioenergy and replaces fossil fuels. The conclusions are summarized in section 6. The appendix (1) clarifies the importance of considering not only a single-harvest event in the case that a permanently higher harvest level is to be analyzed, and (2) considers two scenarios where greater harvest is achieved through expansion of the harvested area, not reducing the rotation length as considered in sections 4 and 5. Finally, the appendix provides a complete model description with all parameter values.

2. A stylized boreal forest

The typical life cycle of a Norwegian spruce tree includes a growth phase that lasts about 100 years and then a phase in which the mass remains relatively stable for a further 100 years. The tree then dies, but remains standing for about 30 years before falling to the ground and gradually decaying over the course of the following 100 years.

This long life cycle suggests that it is a mistake to ignore CO_2 emissions generated by wood combustion. However, as should be made clear in the subsequent sections, a forest is a complex system, and forest dynamics cannot be understood by studying individual trees or a single harvest and subsequent regeneration of the felled trees. I have therefore described and analyzed a dynamic stylized forest. The stylized forest considered consists of 75,000 parcels with the same properties, each covering one square kilometer (km^2). More details of the standard parcels are given below, and the simulation results are presented in the two subsequent sections.

The stylized forest's productivity is fairly normal for a boreal forest. The accumulation of dead and living wood in each parcel of forest after felling and replanting is shown in Figure 1.[2] Natural losses are low until the trees are 80–90 years old, increase sharply until they are 150 years old, and then gradually stabilize. Note that the periodization (time unit) in the model is 5 years.

Changes in the stock of wood after 130 years are uncertain. A number of articles assume that older boreal forests are insignificant carbon sinks (Carey et al. 2001, Luyssaert et al. (2008), Pregitzer et al. 2004, Seely et al. 2002), but do not claim that the carbon stocks of older forests are declining very significantly. Owing to the uncertainty with regard to the carbon stock of old forest, I have nevertheless, as a conservative estimate, assumed that the stock of wood, and thus the carbon stored in the biomass, declines substantially as a parcel ages (see Figure 1). Less conservative assumptions at this point would have strengthened my conclusions.

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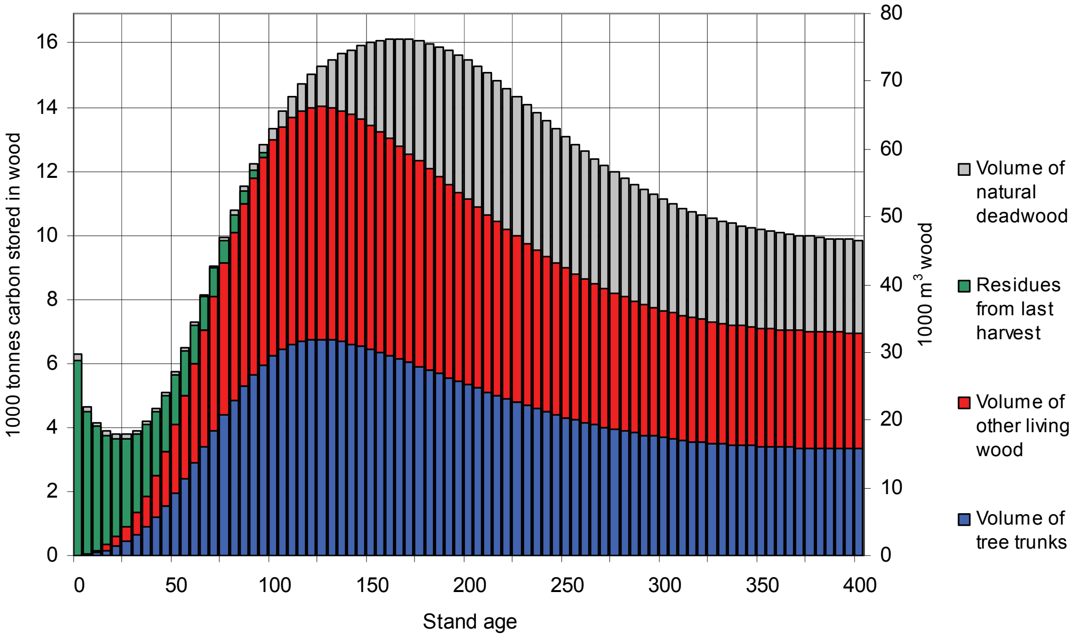
[2] See formulas and parameter values in the Appendix.

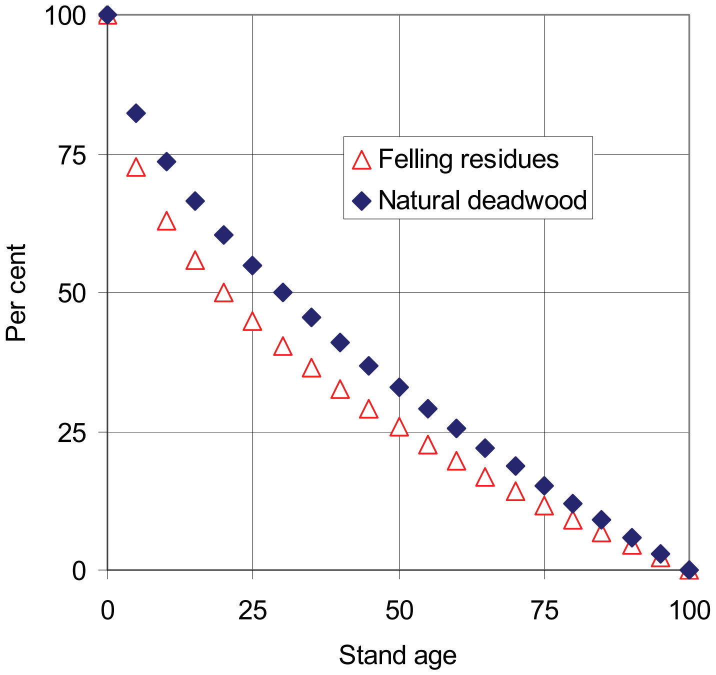
Figure 1. A single parcel. The development of the volumes of tree trunks, other living wood, felling waste and natural deadwood after clearcutting and replanting. Stand age at time of last felling was 90 years



An important point is the role of soil as a carbon sink. In a boreal forest, in contrast to a tropical rain forest, a large share of the carbon is stored in the soil. According to Kjønaas et al. (2000), more than 80 percent of the carbon in Norwegian forests is stored in the soil. An important question is therefore whether harvest is likely to trigger the release of carbon from the soil. As underlined by Fontaine et al. (2000), Friedland and Gillingham (2010), Astrup et al. (2010) and Nilsen et al. (2008), the accumulation and possible release of carbon from the soil are complicated processes that are not easily modeled. I have therefore chosen to ignore the possibility that harvesting may reduce the capacity of the soil as a carbon sink, although Nakane and Lee (1995) and Nilsen et al. (2008) suggest that clearcutting might trigger the release of carbon from the soil, especially if tops and branches are harvested in addition to the trunks. Hence, again my conclusions would have been strengthened if I had relied on less conservative assumptions.

Following Liski et al. (2005), I assumed that deadwood decomposes at the rate shown in Figure 2. Natural dead biomass decomposes rather more slowly than waste from felling because natural deadwood also contains tree trunks, which break down considerably more slowly than branches, tops and roots. In the reference case, 75 percent of all harvest residues and 70 percent of natural deadwood decomposed in 50 years. In the appendix, I present a number of sensitivity simulations with regard to these assumptions. These simulations show that different assumptions at this point do not change the results significantly.

Figure 2. **Remaining share of wood after natural death or clearcutting. The symbols show the proportion of the wood that has not decomposed at the given time**



3. Results: relationship between the length of the rotation cycle and the carbon stock in different steady states

Figure 3 provides important information for a discussion on carbon neutrality. It shows the volume of timber felled annually (curve) and the entire forest's stock of carbon in dead and living wood (columns) for rotation cycles of different lengths (horizontal axis).[3]

It should be noted that Figure 3 considers the entire forest area of 75,000 km^2 and shows the forest in different *steady states*, in the sense that the length of the rotation cycle is constant and has been constant for so long that both the harvest and standing volume are also constant over time.

Figure 3 confirms that the maximum harvest (*volume felled*) is obtained with a rotation cycle of 90 years. The *carbon stock*, on the other hand, reaches a maximum when the rotation cycle is about 250 years (see also Table 1).

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[3] The carbon content of a cubic meter of biomass depends on the wood's density. I assume throughout a density of 423 kg/m^3, and that half of the mass is carbon. This gives 0.211 tonnes carbon per m^3, or 0.774 tonnes CO_2 per m^3 wood used as fuel. For further details, see the appendix.

The stock of carbon is almost twice as large with a 250-year rotation cycle as with a 90-year rotation cycle. This may seem difficult to reconcile with Figure 1, which shows that the stock of carbon in a single parcel of forest reaches a maximum 150 years after clearcutting and replanting. The explanation is that as the length of the rotation cycle increases from 150 to 250 years, there are fewer and fewer parcels that have recently been clearcut. In other words, if the rotation cycle is long, a large share of the parcels of land will at any point in time carry a large stock of wood. If the rotation cycle is short, on the other hand, a large proportion of the forest will at any point in time be relatively recently felled, and its stock of wood will be correspondingly small.

Figure 3 indicates that it is misleading to claim that wood provides carbon-neutral bioenergy, even in the long term. It shows that if the harvest is permanently large, which requires short rotation cycles, the carbon pool of the forest will be permanently small. In contrast, if the annual harvest is small, with correspondingly long rotation cycles, the carbon pool will be permanently large. With a 90-year rotation cycle, for example, an area of 833 km^2 can be felled each year, giving an annual harvest of 22.3 million cubic meters (Mm^3) timber and 471 million tonnes carbon (MtC) stored in dead and living wood. With a 250-year rotation cycle, 300 km^2 can be felled annually and the annual harvest is only 6.1 Mm^3; the carbon stored in dead and living wood, on the other hand, rises to 900 MtC (see Table 1).

Table 1. Two different steady states

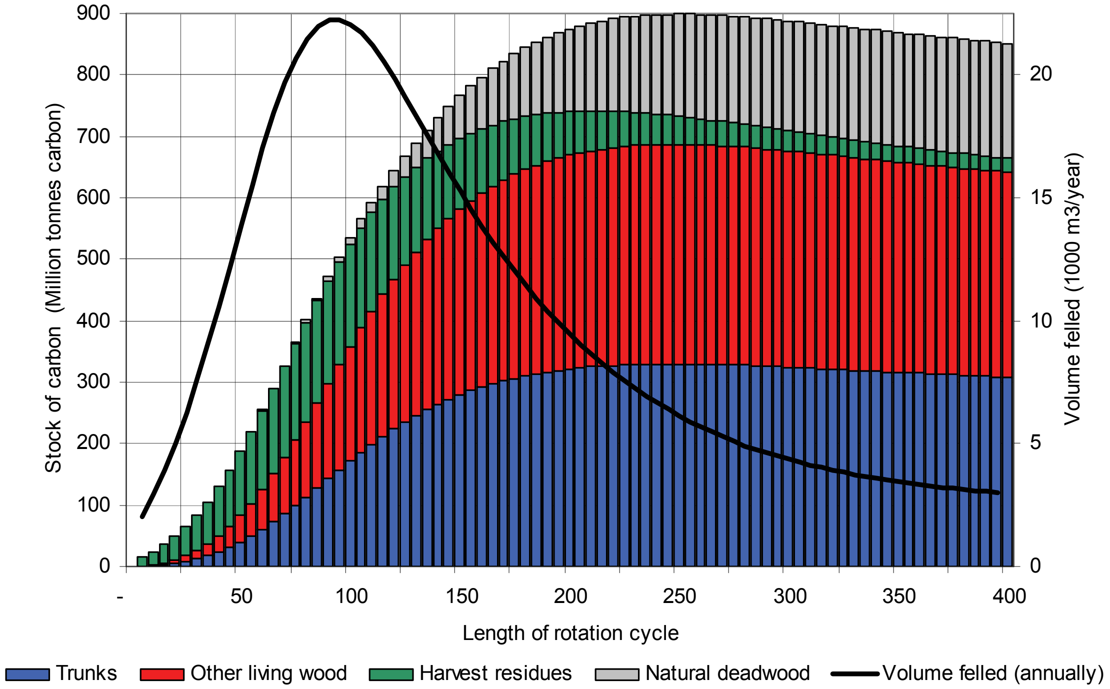
	Length of the rotation cycle (years)	Annual harvest (Mm^3)	Area harvested annually (km^2)	Carbon stored in dead and living biomass (MtC)
Steady state with maximum harvest	90	22.3	833	471
Steady state with maximum carbon stock	250	6.1	300	900

In other words, increasing the harvest to a higher level on a permanent basis does not merely result in a *temporary* drop in the forest's carbon stock that will in the long term be entirely counterbalanced by CO_2 uptake by the forest. On the contrary, a *permanent* increase in the harvest results in a *permanently* lower forest carbon stock. Phrased differently, with a higher annual harvest level, the rotation cycle must be shortened. A shorter rotation cycle results in little carbon stock. Hence, increasing the harvest level is not a carbon-neutral change, either in the short term or in the long term.

This also shows that the question of carbon neutrality cannot be resolved by studying the effect of a single harvest in a single year with subsequent planting. Such a single-event perspective is an oversimplification that does not incorporate the important long-term dynamic effects on the forest's carbon stock (see Appendix A1 for further discussion).

At this point, the report on biomass sustainability presented by the Manomet Center for Conservation Sciences (2010) should be mentioned. This report considers only a single-harvest event rather than conducting "...a more complicated series of repeated harvest entries." (ibid. p. 85). The Manomet report is important along different lines as it contains new information and provides an interesting perspective on the carbon neutrality of wood energy. However, the report's relative optimistic conclusions with regard to the time lag between harvest, the released volume of carbon dioxide and the payback time of a carbon debt reflects the report's single-harvest approach and therefore does not take into account important features of the long-term effect of a higher level of harvest on the forest's carbon stock. As shown in Appendix A1, the payback time is approximately doubled if a series of subsequent harvest events are considered instead of a single-harvest event.

Figure 3. The entire stylized forest. Annual volume of timber felled (black curve) and quantity of carbon stored in dead and living wood (columns) in different steady states for rotation cycles of different lengths



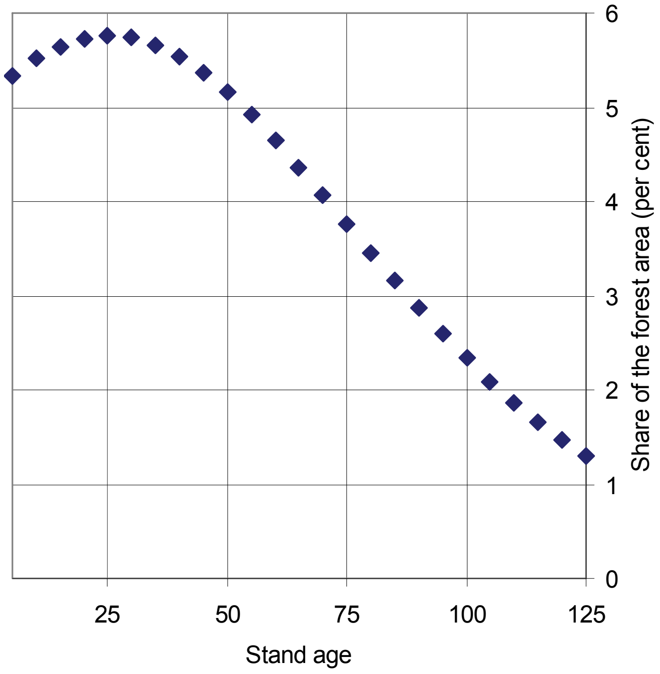
4. Short-term and long-term effects of increasing the harvest

The previous section considered the carbon stock of a forest in a steady state in the sense that the rotation cycles were constant over time, giving the forest an even age structure. This section provides more realism by describing the short-term and long-term effects of increasing the harvest in a forest with an uneven age structure similar to the age structure found for a Norwegian forest.

The Norwegian forest has a high proportion of young trees. The assumed age structure in the starting year (2005) of the stylized example implies that 37 percent of the area was felled and replanted less than 30 years ago, while 21 percent of the area was felled and replanted more than 80 years ago. Hence, 42 percent of the forest is between 30 and 80 years old. For details, see Figure 4 and the appendix. In the starting year, the total volume of living wood (trunks) is assumed to be 776 Mm^3, the annual harvest is 10 Mm^3, and the harvest has been at this level for some decades. It follows that the forest's carbon stock (not including soil carbon) is 425 MtC in the starting year.

I now assume that the owners decide to increase the annual harvest by 3 Mm^3, to 13 Mm^3, starting in 2010. Two large-harvest scenarios are considered: one where only the trunks are harvested and a second where also tops and branches that belong to the additional 3 Mm^3 of trunks are harvested.

Figure 4. Age structure of the stylized forest in the starting year 2005



The chosen numerical example has relevance, as the annual harvest from Norwegian forests has varied around 10 Mm^3 for several decades. However, the Norwegian government wants to increase the harvest to increase the supply of bioenergy. The report on proposed Norwegian climate policies, Klimakur 2020 (2010), therefore uses an increase in the annual harvest to 13 Mm^3 as its reference scenario and main proposal.

What effect does a higher harvest level have?

Given the assumed age structure, with a large share of young trees in the forest, and because the annual harvest is limited to 10 Mm^3 in the reference scenario, the forest's carbon stock increases until the middle of the 22nd century (see Figure 5). Moreover, even if the harvest is increased to 13 Mm^3, the forest's carbon stock increases over this period, although at a lower rate. The vertical distances between the upper curve and the two lower curves in Figure 5 show the accumulated net reduction in the forest's carbon stock as a result of the greater harvest.

Figure 5. Forest carbon stock in the three scenarios considered in sections 4 and 5

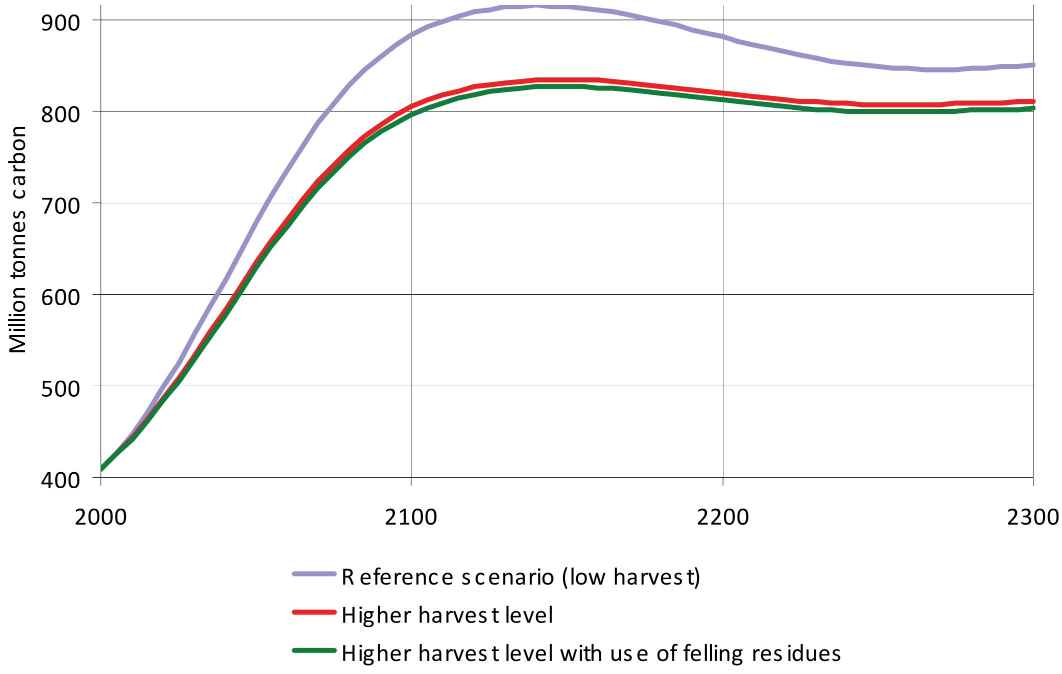
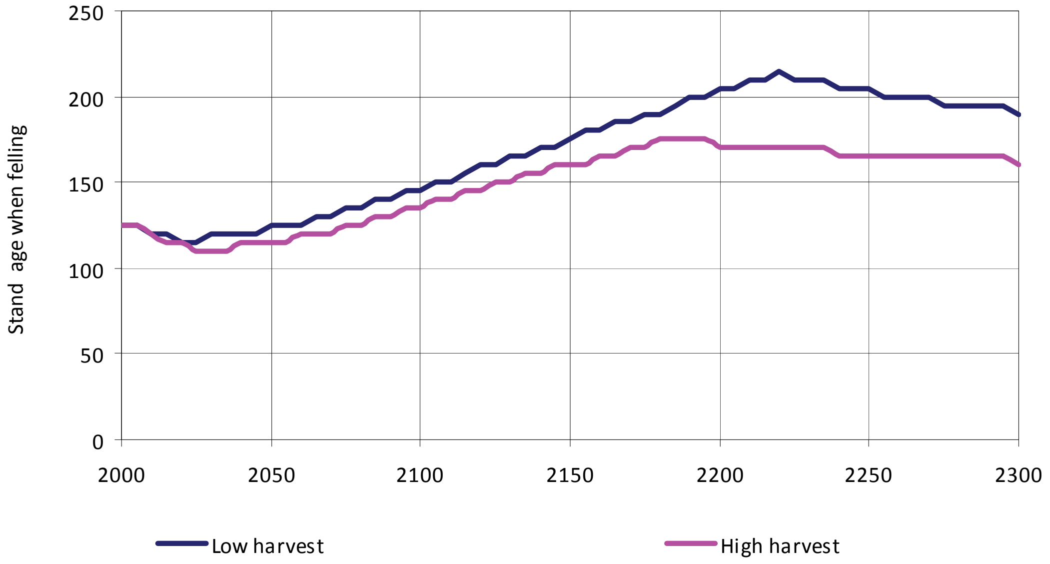


Figure 5 also shows that if tops and branches are harvested, the forest's carbon stock will be permanently somewhat lower than in the case where all harvest residues are left in the forest. This is because the amount of carbon stored in harvest residues is somewhat lower when tops and branches are harvested than when all harvest residues are left in the forest. This stock effect implies that the mitigation effect of harvesting residues is not as high as one would expect if the stock effect is ignored.

It is important to note that Figure 3 shows different steady-state situations for rotation cycles of different lengths, whereas Figures 5 and 6 show the transition from one steady state to another.[4]

For further clarification, consider the reference (small-harvest) scenario as illustrated by the upper curve in Figure 5. The figure shows that by 2100, the forest's carbon stock has more than doubled from the 2005 level, to 883 MtC (see also Table 2). However, Figure 5 also shows that in the larger-harvest scenario with no use of harvest residues, the carbon stock is only 804 MtC in 2100. In other words, the increase in the harvest has resulted in a forest carbon stock that is 79 MtC lower in 2100 than it would have been with the lower harvest level. In the case where tops and branches are harvested and used for energy purposes, the carbon stock of the forest in 2100 is 87 MtC lower than in the small-harvest scenario.

Figure 6. Stand age at the time of felling in the two scenarios



If we assume combustion of all the harvested trunks together with associated tops and branches, the forest's accumulated net carbon capture and storage (CCS) in the period 2005 to 2100 is 87 MtC lower under the large-harvest scenario than it would have been under the small-harvest scenario. In the case where harvest residues are left to decompose in the forest, the forest's CCS is 79 MtC less than that under the small-harvest scenario.

Figure 6 provides information on the stand age at the time of felling in the two scenarios. In both scenarios, the rotation period increases until around the year 2200.

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[4] For an analysis of different steady states, see Liski et al. (2005).

5. Reducing the use of fossil energy by increasing the use of wood energy

The argument for felling more timber is precisely that using wood as a source of bioenergy can reduce the use of fossil energy and thus cut CO_2 emissions. The question is whether the reduction in the forest carbon stock is larger or smaller than the reduction in CO_2 emissions achieved by reducing fossil fuel use. This is discussed in the following.

The previous section considered how felling affects forest biomass and thus the carbon stock in the forest. In this section, I consider the extent to which increasing the timber harvest for bioenergy production can replace the use of fossil energy. Taking account of both the replacement effect on fossil fuel combustion and the effects on the forest's carbon stock, it is possible to calculate the net CO_2 effects of increased logging.

The quantity of fossil energy that wood fuels can replace varies widely depending on precisely which technologies are involved. Processing wood, for example to make pellets, often results in substantial CO_2 emissions. Here I discuss two examples that show how two different types of wood fuels will affect net CO_2 emissions.

In the first case, I have assumed that the wood is used as the raw material for manufacturing pellets. The pellets then replace coal in power plants. This is a relevant example because this is taking place on an increasing scale in Europe because power producers are not supposed to acquire and surrender allowances for emissions resulting from the combustion of bioenergy. In Norway, it has special relevance as the world's second-largest wood pellet production plant (BioWood Norway) has recently been established on the west coast of Norway, and will manufacture pellets on a large scale for this purpose. Sjølie and Solberg (2009) present a life-cycle inventory of BioWood Norway in which they assume that wood fuel is carbon neutral and conclude that replacing fossil fuel with wood pellets is a good way of reducing CO_2 emissions. The same exercise is carried out below, but taking the consequences of logging for the forest's carbon stock into account. As will be demonstrated, this leads to the conclusion that pellet production based on wood from boreal forests is likely to create a significant carbon debt and a long payback time, even if this bioenergy replace coal in power plants.

In the second example, I look at the use of wood to produce second-generation biodiesel. This example is relevant as it is common to consider second-generation liquid biofuels based on wood as a promising option (see, for example, Hill et al. (2007). Moreover, Klimakur 2020 (2010) presents ambitious scenarios for the production of second-generation liquid biofuels based on wood.

The exact volumes of CO_2 emissions that can be eliminated using wood energy are of great importance. For the processing of wood into pellets and replacement of coal in a coal-fired power plant, I have used the calculations of Sjølie and Solberg (2009) as a basis. The starting point is that 1 m^3 of wood contains 0.423 tonnes of dry mass. Fifty percent of the dry mass is carbon. Hence, 1 m^3 of wood is assumed to contain 0.212 tonnes of C, or generate 0.776 tonnes of CO_2 through combustion. With the chosen assumptions, I find that using 1 m^3 of wood, processed to pellets, instead of coal in a power plant can eliminate 0.496 tonnes of fossil-generated CO_2 emissions. The method used to calculate this figure is described in further detail in the appendix.

To calculate the volume of fossil emissions that can be eliminated using second-generation biofuels, I followed Klimakur 2020 (2010), p 186. This report concludes that using 1 m^3 of wood processed to second-generation liquid biofuel can eliminate 0.2 tonnes of CO_2 emissions generated through the combustion of liquid fossil fuel.[5]

We are now ready to calculate the net effect of the increased harvest on accumulated CO_2 emissions. It is possible to gain a visual impression of the results from Figure 7 by comparing the lines with the curves. The lines show the *accumulated* fossil CO_2 emissions that can be eliminated by increasing the volume of timber harvested and using this harvest to replace fossil fuels in the two ways discussed above.

To go into detail, it is assumed that the annual harvest increases by 3 Mm^3. In this section, I focus on the case where tops and branches are harvested together with the 3 Mm^3 of trunks. It is assumed that trunks constitute 48 percent of the trees' biomass, while tops and branches together account for 18 percent of the total biomass. This means that the overall increase in the annual harvest is 4.1 Mm^3 when tops and branches are harvested.

Firstly, consider the case where the wood is processed to pellets and replaces coal in a power plant. In that case each cubic meter of wood eliminates 0.496 tonnes of fossil-generated CO_2 emissions (see the appendix). This means that 2.03 $MtCO_2$ or 0.55 MtC fossil emissions are eliminated each year. Hence, by 2100, fossil CO_2 emissions corresponding to 53 MtC have been eliminated (see the level of the green line in 2100 in Figure 7 and Table 2).

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[5] This is without use of harvest residues. When I include the harvesting of tops and branches, the replacement effect is 37 percent higher.

Table 2. Carbon stock, emission reductions and carbon debt in the scenarios considered in section 4 (million tonnes of carbon)

	2005	2100	2200	2300
Carbon stock in small-harvest scenario	425	883	881	851
Carbon stock in large-harvest scenario with use of harvest residues	425	796	812	803
Drop in carbon stock due to increased harvest	0	87	69	48
Accumulated reductions in carbon emissions from coal combustion due to increased harvest	0	53	109	165
Carbon debt—wood fuels replace coal	0	34	–40	–117
Accumulated reductions in carbon emissions from combustion of fossil oil (petrol or diesel) due to increased harvest	0	21	44	66
Carbon debt—wood fuels replace liquid fossil fuels	0	65	25	–18

The increased harvest means that the carbon stock of the forest by 2100 is 87 MtC less than it would have been if the annual harvest had been maintained at 10 Mm^3 (see Figures 5 and 7). Subtracting 53 MtC (substitution), we have that in the pellets case, by 2100 the increase in the harvest has caused a net carbon debt of 34 MtC, to use a term introduced by Fargione et al. (2008). In other words, although increasing the harvest eliminates fossil CO_2 emissions from coal combustion corresponding to 53 MtC, the net accumulated release of carbon to the atmosphere will be 34 MtC higher in the period 2010–2100 in the large-harvest scenario than in the small-harvest scenario.

The blue curve in Figure 7, the elevation of which is equal to the vertical distance between the blue and green curves in Figure 5, shows the difference in the carbon stock between the large- and small-harvest scenarios.

The carbon debt in the pellets case is equal to the vertical distance between the blue curve and the green line in Figure 7. The development of the carbon debt is shown in Figure 8. This figure shows that the carbon debt is declining in 2100 and becomes negative around 2160; that is, 150 years after the increase in the harvest. Hence, the analysis suggests that increasing the harvest and the use of wood fuels to replace coal in power plants could, for a long period of time, result in significantly greater CO_2 emissions than the combustion of the coal that the increased harvest replaces.

Figure 7. **The two straight lines show the accumulated reductions in CO_2 emissions from combustion of fossil energy achieved by increasing the supply of bioenergy through a higher harvest level. It is assumed that both tops and branches are harvested together with the trunks. The blue curve in Figure 7 shows the difference in the carbon stock between the small- and large-harvest scenarios**

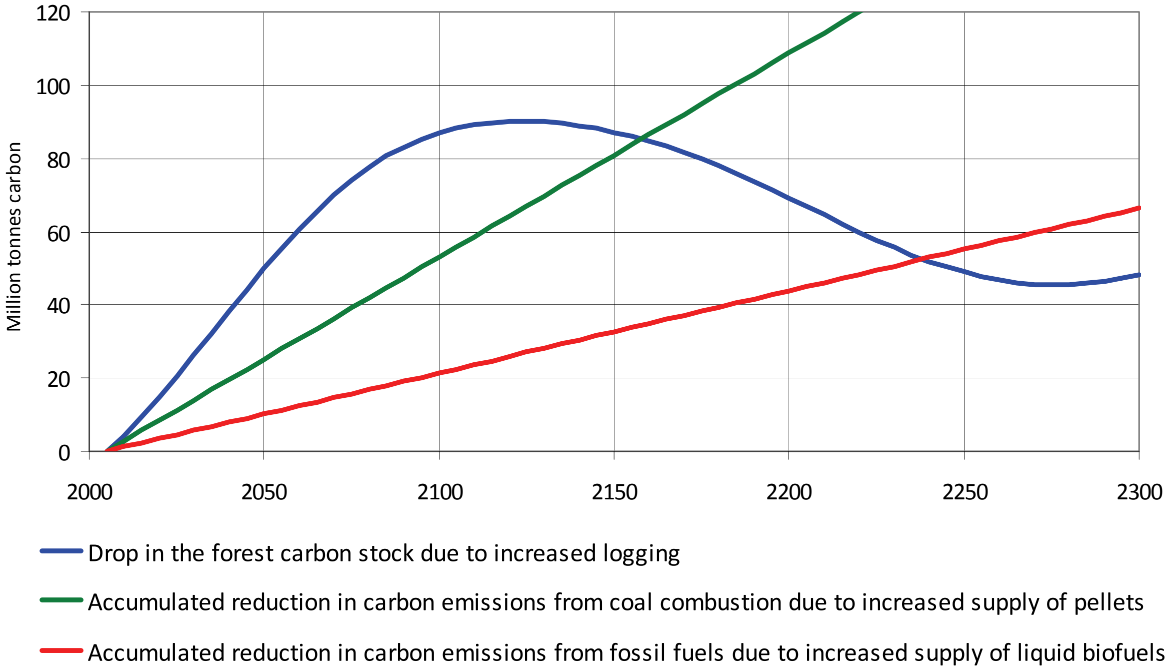
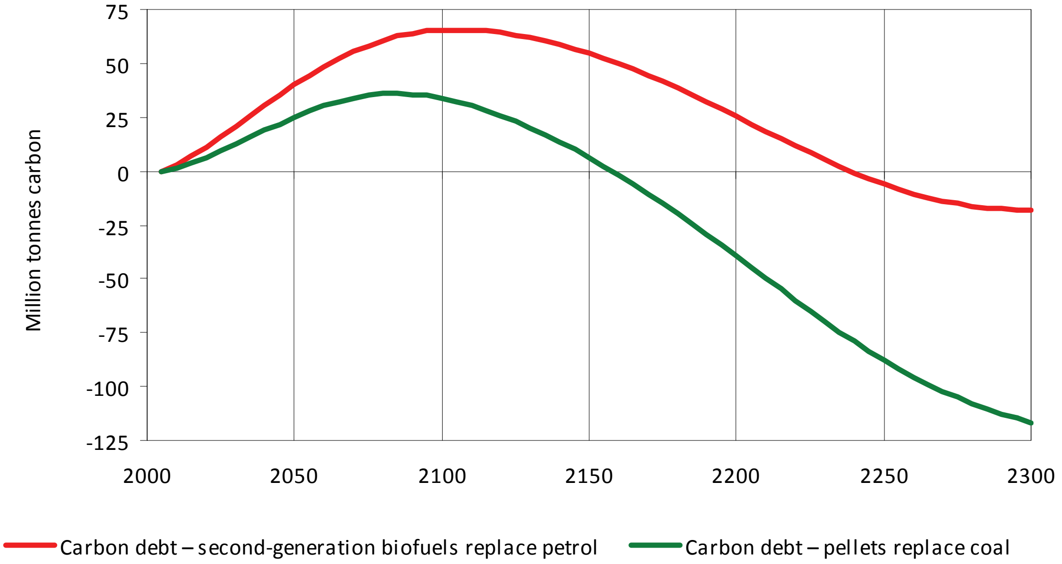


Figure 8. **Development of the carbon debt due to increased harvest when the increased harvest is used to replace different types of fossil fuels. In both, tops and branches are harvested together with the trunks**



Both Sjølie and Solberg (2009) and Sjølie et al. (2010) conclude that increasing the harvest to replace coal in coal-fired power plants will *reduce* CO_2 emissions from day one. My figures for the replacement of coal agree to a large extent with the numerical assumptions used by Sjølie and Solberg (2009) and Sjølie et al. (2010). However, these papers make the assumption that wood fuels are carbon neutral, and CO_2 emissions from the combustion of wood are accounted as zero in their calculations. The analysis presented in this paper shows that as more realistic estimates of these emissions and the dynamics of the forest are included in the analysis, the results of Sjølie and Solberg (2009) are reversed.

Secondly, consider the effect of using the extra harvest of wood as raw material in the production of second-generation biodiesel. In that case each cubic meter of wood eliminates 0.2 tonnes of fossil-generated CO_2 emissions (see the appendix). This means that 0.8 $MtCO_2$ or 0.23 MtC fossil emissions are eliminated each year. Hence, by 2100, fossil CO_2 emissions corresponding to 21 MtC have been eliminated, see the level of the red line in 2100 in Figure 7, which shows the *accumulated* substitution effect in this case.

The red line is at a lower level than the blue curve throughout both the 21st and the 22nd centuries. Thus, the calculations indicate that using second-generation biodiesel produced from boreal timber rather than continuing to use fossil diesel may actually *increase* the net release of CO_2 for an even longer period, and generate a carbon debt that will be repaid only after more than two centuries. This is in contrast to the results obtained by assuming that wood is a climate-neutral fuel.
Summing up, this section found that if wood fuels replace coal in power plants, the payback time will be 150 years. If wood is used as raw material for second-generation liquid biofuels that replace fossil liquid fuels, the payback time is estimated to be 230 years.

6. Final comments

The increased use of bioenergy is often considered an important part of the global mitigation strategy against climate change (see, for example, IPCC (2000). The generation of biomass in boreal forests is significant and could potentially serve as an important source for an increased supply of bioenergy.

This paper considers a stylized model of the Norwegian forest. In the numerical examples presented in this paper, the harvest is increased by 30 percent, while the forest increment is still positive over the whole 21st century. Nevertheless, the increase in the harvest means that the carbon stock in the stylized forest stabilizes at a different level, as would be expected. Hence, even if the forest increment is positive, wood harvesting and combustion are not carbon-neutral activities.

The paper also presents calculations illustrating the net effect on the CO_2 release of increased logging for the sole purpose of increasing the supply of bioenergy. Two examples are described: processing wood to pellets for use in coal-fired power plants, and processing wood to biodiesel, which is used to replace fossil diesel.

In both cases, the increase in the harvest is found to give a greater drop in the forest's CCS than the reduction in CO_2 emissions caused by replacing fossil fuels with biofuels. This situation persists for several decades, creating a carbon debt that is not repaid until some decades into the 22nd or 23rd century.

The paper's main finding is that increasing the use of wood from a boreal forest to replace coal in power plants will create a carbon debt that will only be repaid after 150 years. If the wood is used to produce second-generation liquid biofuels and replaces fossil diesel, the payback time of the carbon debt is 230 years.

In addition, it is important to remember that the analyses presented here do not take into account the effect of providing subsidies for various alternative forms of energy as a means of reducing the use of fossil energy. Such subsidies tend to increase overall energy use. If this is taken into account, the emission-increasing effect of using wood as energy will become even more pronounced. A complete analysis should also include such effects.

An uncertain aspect of the parameterization of the model is the determination of changes in the volume of natural deadwood over time. Sensitivity calculations were therefore carried out to test the effect of varying the rate of decay for natural deadwood. These simulations show that the parameterization is not a critical factor (see the appendix).

Nevertheless, it should be stressed that the purpose of this paper is not to provide definitive answers but to draw attention to the importance of taking both short- and long-term dynamic effects of increasing the timber harvest more fully into account when evaluating the mitigation effect of increasing the use of energy from wood combustion.

It should also be underlined that the analysis presented here does not make arguments against the use of bioenergy from boreal forests in general. The paper considers increased logging in boreal forests for the sole purpose of increasing the use of bioenergy. If bioenergy is obtained through increased use of waste from different forest-related industries, the CO_2 effects are probably positive.

Nevertheless, the commonly applied assumption that wood fuels are climate neutral is not tenable. If this assumption is reevaluated, it may also be necessary to reevaluate the current taxes and subsidies that apply to bioenergy and forestry. It is not at all clear whether current policy takes sufficient account of the potential of forests as a carbon sink or of the fact that burning wood results in CO_2 emissions. As highlighted in Searchinger et al. (2009), for example, putting a high price on CO_2 emissions from fossil energy emissions while considering bioenergy to be carbon neutral would create strong incentives to clear land.

The claim that using wood fuels is carbon neutral is based on the approximation that logging has a negligible effect on the forest's carbon stock. This would be a reasonable approximation if there were a very short time lag between felling and full regrowth. The carbon-neutrality claim ignores the significance of this time lag and the fact that there will be a permanent reduction in the volume of both dead and living biomass in the forest if the harvest is permanently increased. Thus, the common assumption that using wood as bioenergy is carbon neutral also means that it is assumed that all the effects on the forest's carbon stock are so small that they can be ignored.

References

Astrup, R., L. Dalsgaard, R. Eriksen, and G. Hylen (2010): Utviklingsscenarioer for karbonbinding i Norges skoger,(Development scenario for carbon capture in Norwegian forests). Unpublished memo from the Norwegian Forest and Landscape Institute, Ås.

Bright, R. M., and A. H. Strømman (2009): Life cycle assessment of second generation bioethanol produced from Scandinavian boreal forest resources. *Journal of Industrial Ecology* **13**, 514–530.

Carey, E.V., A. Sala, R. Keane, and R.M. Callaway (2001): Are old forests underestimated as global carbon sinks? *Global Change Biology* 7, 339–344.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne (2008): Land clearing and the biofuel carbon debt. *Science* 319, 1235–1238.

Fontaine, S., S. Barot, P. Barré, N. Bdioui, B. Mary, and C. Rumpel (2007): Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature* 450, 277–281.

Friedland, A. J., and K. T. Gillingham (2010): Carbon accounting a tricky business. *Science* 327, 411–412.

Gibbs, H. K., A. S. Ruesch, F. Achard, M. K. Clayton, P. Holmgren, N. Ramankutty, and J. A. Foley (2010): Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings from the National Academy of Sciences* 107, 16732–16737.

Gurgel, A. J., M. Reilly, and S. Paltsev (2007): Potential land use implications of a global biofuels industry. *Journal of Agricultural & Food Industrial Organization* 5, 1–34.

Goksøyr, H. (2007): Skogsvirke som brensel øker CO_2-problemet (Wood fuels exacerbate the CO_2 problem). *Teknisk ukeblad* 22 August 2007.

Hartmann, D., and M. Kaltschmitt (1999): Electricity generation from solid biomass via co-combustion with coal energy and emission balances from a German case study. *Biomass and Bioenergy* 16, 397–406.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany (2006): Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings from the National Academy of Sciences* 103, 11206–11210.

Hohle, E. E. (2001): *Bioenergi – Miljø, teknikk, marked*. Energigården.

Holtsmark, B. (2010): Om tømmerhogst og klimanøytralitet (On wood harvest and climate neutrality). *Økonomiske analyser* 3, 10–18.

Klimakur 2020 (2010): Tiltak og virkemidler for å nå norske klimamål mot 2020, (Efforts and policies for Norwegian climate goals toward 2020). The Norwegian Climate and Pollution Agency, Norwegian Water Resources and Energy Directorate, The Norwegian Petroleum Directorate, Statistics Norway, The Norwegian Public Road Administration. *Report* TA2590.

IPCC (2000): Special Report on Emissions Scenarios, Working Group III, Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

Kjønaas, O. J., H. Aalde, L. S. Dalen, H. A. de Wit, T. Eldhuset, and B. H. Øyen (2000): Carbon stocks in Norwegian forested systems. *Biotechnology, Agronomt, Society and Environment* **4**, 311–314.

Lapola, D. M., R. Schaldach, J. Alcamo, A. Bondeau, J. Koch, C. Koelking, and J. A. Priess (2010): Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings from the National Academy of Sciences* 103, 11206–11210.

Liski, J., A. Pussinen, K. Pingoud, R Mäkipää, and T. Karjalainen (2001): Which rotation length is favourable to carbon sequestration? *Canadian Journal for Forest Research* **31**, 2004–2013.

Liski, T. P., M. Peltoniemi, and R. Sievänen (2005): Carbon and decomposition model Yasso for forest soils. *Ecological Modelling* **189**, 168–182.

Luyssaert, S., E. D. Schulze, A. Börner, A. Knohl, D. Hessenmöller, B. E. Law, P. Ciais, and J. Grace (2008): Old-growth forests as global carbon sinks. *Nature* **455**, 213–215.

Melillo, J. M., J. M. Reilly, D. W. Kicklighter, A. C. Gurgel, T. W. Cronin, S. Paltsev, B. S. Felzer, X. Wang, A. P. Sokolov, and C. A. Schlosser (2009): Indirect emissions from biofuels: how important? *Science* 326, 1397–1399.

Manomet Center for Conservation Sciences (2010): Massachusetts Biomass Sustainability and Carbon Policy Study: Report to the Commonwealth of Massachusetts Department of Energy Resources. Walker, T. (Ed.). Natural Capital Initiative Report NCI-2010-03. Brunswick, ME, USA.

Nakane, K., and N. J. Lee (1995): Simulation of soil carbon cycling and carbon balance following clear-cutting in a mid-temperate forest and contribution to the sink of atmospheric CO_2. *Vegetatio* 121, 147–156.

Nilsen, P., K. Hobbelstad, and N. Clarke (2008): Opptak og utslipp av CO_2 i skog. (Capture and Emission of CO_2 from Norwegian forests) Norwegian Forest and Landscape Institute, report no. 06/2008.

Petersen, A. K., and B. Solberg (2005): Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. *Forest Policy and Economics* **7**, 249–259.

Pregitzer, K. S., and E. S. Euskirchen (2004): Carbon cycling and storage in world forests: biome patterns related to forest age. *Global Change Biology* 10, 2052–2077.

Raymer, A. K. P. (2006): A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass and Bioenergy* **30**, 605–617.

Searchinger T. D., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. Yu (2008): Use of US croplands for biofuels increases greenhouse gas through emissions from land-use change. *Science* **319**, 1238–1240.

Searchinger T. D., S.P. Hamburg, J. Melillo, W. Chameides, P. Havlik, D.M. Kammen, G.E. Likens, R.N. Lubowski, M. Obersteiner, M. Oppenheimer, G.P. Robertson, W.H. Schlesinger, G.D. Tilman (2009): Fixing a critical climate accounting error. *Science* **326**, 527–528.

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

Sjølie, H. K., E. Trømborg, B. Solberg, and T. F. Bolkesjø (2010): Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway, *Forest Policy and Economics* 12, 57–66.

Sjølie, H. K., and B. Solberg (2009): Greenhouse Gas Implications by Production of Wood Pellets at the BioWood Norway plant at Averøy, Norway. Report drawn up for BioWood Norway. Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences.

Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S. J. Smith, A. Janetos, and J. Edmonds (2009): Implications of limiting CO_2 concentrations for land use and energy. Science 324, 1183–1186.

Zhang, Y., J. McKechnie, D. Cormier, R. Lyng, W. Mabee, A. Ogino, and H. I. MacLean (2010): Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada. *Environmental Science & Technology* **44**, 538–544.

Appendix A

A1. Single-harvest analyses vs. multiple-harvest analyses

As mentioned in section 3, the Manomet report (2010) presented an interesting analysis of a single-harvest event and its payback time. In this first section of the appendix, we demonstrate that the payback time determined from such a single-harvest analysis is approximately half the payback time determined from analysis of a series of subsequent harvest events.

The starting point for this paper is a comparison of two main scenarios, one with a low harvest level (10 Mm^3/year) and one with a high harvest level (13 Mm^3/year). In both scenarios, the harvest is constant over the entire considered time frame (2010–2300).

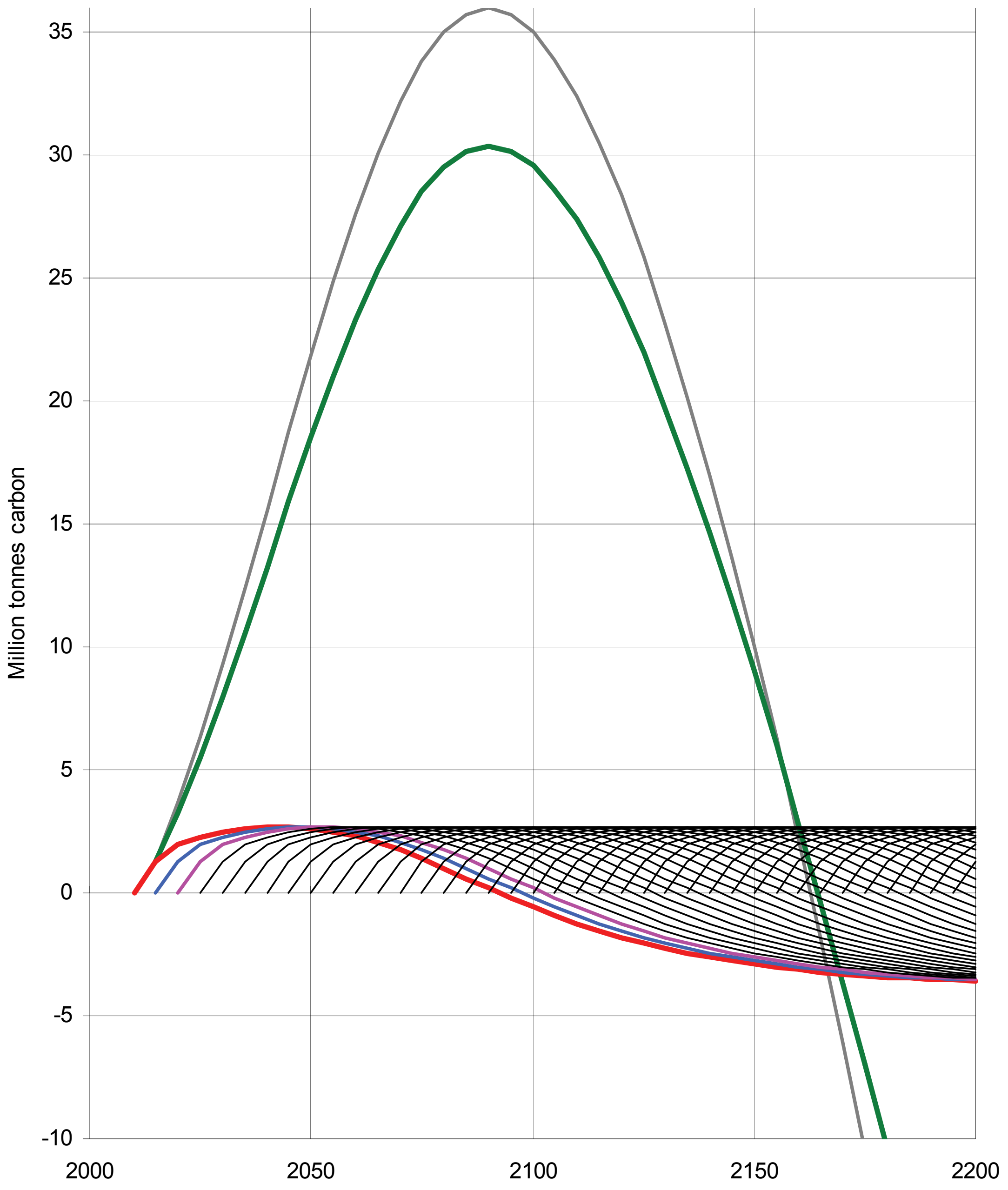
Figure 8 shows the development of the carbon debt from the permanently increased harvest, both in the case of second-generation liquid biofuels and in the case of pellets/coal. The upper gray curve in Figure A1 reproduces the development of the carbon debt in the latter case. We note that the carbon debt is repaid in 2160; that is, after 150 years.

However, the red curve in Figure A1 shows the development of the carbon debt of a corresponding single-harvest taking place in 2010–2014 with an annual harvest of 3 Mm^3 over this five-year period. From 2015 onward, it is assumed that the annual harvest is 10 Mm^3. In other words, the red curve in Figure A1 shows the carbon debt of a single harvest of 15 Mm^3 taking place in the period 2010–2014. This gives a very different result, with the carbon debt of this single-harvest event being fully repaid in 2090; that is, after only 80 years.

Hence, the carbon debt of a single-harvest event is repaid significantly sooner than the carbon debt of the permanently increased harvest level.

How can this result be explained? Consider the blue curve in Figure A1. This curve represents the carbon debt of the single event of harvesting 15 Mm^3 in the period 2015–2019. Both before 2015 and after 2019, the annual harvest is 10 Mm^3/year. The carbon debt of this harvest is repaid after 80 years; that is, in 2095. Correspondingly, the pink curve in Figure A1 represents the carbon debt of a single harvest of 15 Mm^3 in the period 2020–2024. The carbon debt of this harvest is fully repaid in 2100. All black curves in the same manner represent the carbon debt of corresponding subsequent single-harvest events.

Figure A1. **Development of the total carbon debt from increased harvest (gray curve) and the carbon debt generated by subsequent identical single-harvest events. The green curve represents the sum of the carbon debt of all the single-harvest events**



However, we want to know at what point in time we should expect that the *permanently* increased harvest level will start to provide climate benefits; that is, when the carbon debt is repaid for such a long-term harvest strategy. We then have to add up (vertically) the carbon debt generated by all single-harvest events. The aggregate carbon debt is represented by the green curve in Figure A1, indicating a payback time of 150 years instead of 80 years.[6]

This difference underlines that single-harvest analysis does not provide complete answers if we want to analyze the consequences of increased harvest levels for the foreseeable future.

A2. Extending the area harvested

Sections 4 and 5 considered a case where the large-harvest scenario did not imply an extension of the area harvested. Instead, increased harvest was achieved through lowering the length of the rotation cycles.

This section of the appendix, on the other hand, considers two scenarios where increased harvest does not mean any change in the rotation period for the area already harvested. Instead, a large-harvest scenario means an extension of the area that is harvested.

In the small-harvest scenario, the harvest is 10 Mm^3, as in the case considered in sections 4 and 5. However, only 45.5 percent or 34,000 km^2 of the forest is harvested. In the small-harvest scenario, there is no harvest outside this area.

To increase the harvest from 10 to 13 Mm^3, an additional area of 7000 km^2 is harvested. Hence, this section analyzes this limited area only, as the harvest in the rest of the forest is identical in the scenarios considered here.

The considered area has an age distribution at the outset as described in Figure 4.

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[6] The green curve differs from the gray curve owing to a simplification made here. The red curve represents a real model simulation of a single-harvest event taking place in 2010–2014. The other single-harvest curves are all identical to the red curve, except for their different starting points. However, a single-harvest event at one point in time affects the dynamics of the forest and thus the standing age of the available parcels for later single-harvest events, and so forth. Therefore, in reality, identical subsequent single-harvest events are an impossibility. Hence, summation based on a set of identical subsequent single-harvest carbon-debt curves will not give the same results as a consistent simulation as was carried out in sections 4 and 5. Therefore, the green and gray curves in Figure A1 differ. Nevertheless, Figure A1 provides insights into why the carbon debt of a single-harvest event differs from the carbon debt of a permanent larger harvest.

In addition to a scenario with *no harvest* in this area, two different harvest scenarios are considered in this section, one *conservative* and one *optimistic*. In both harvest scenarios, the annual harvested volume is 3 Mm^3.

The *optimistic* harvest scenario assumes that after clearcutting and replanting, the density of trees on the harvested parcels is 25 percent higher than the previous density of the standard parcels as described in section 2, Figure 1. In other words, in the *optimistic* scenario, the stock of trunks and other living biomass on any parcel that has undergone clearcutting and replanting after 2010 is 25 percent higher than would have been the case if the regeneration of the parcels had followed the path described in Figure 1.

The *optimistic* harvest scenario is motivated by claims that harvest is an opportunity to replace sparse forests with more productive forests.

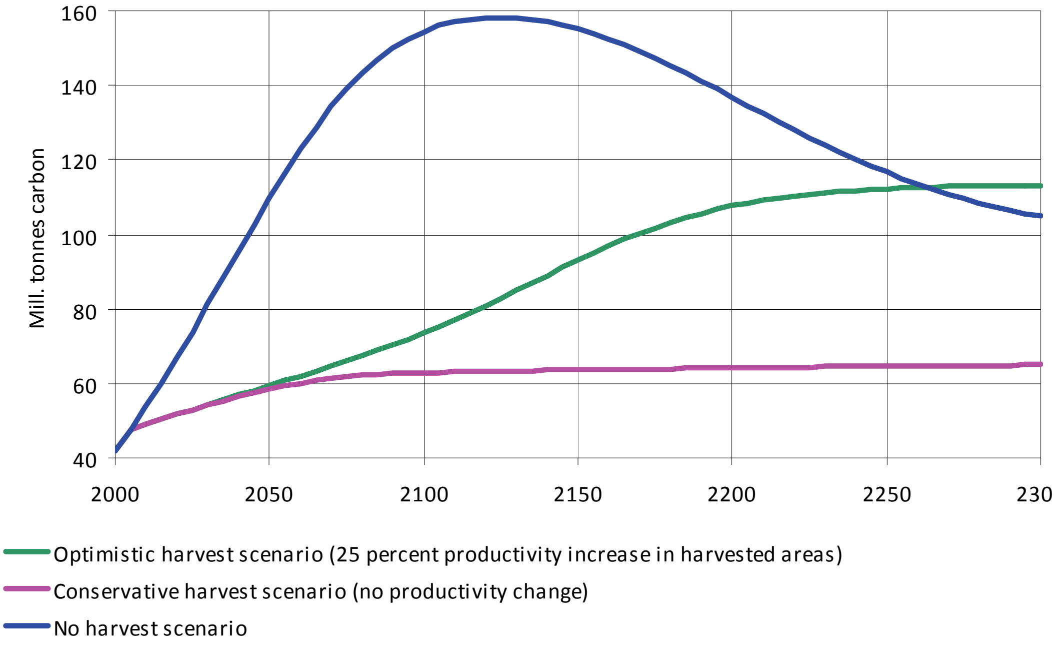
In the *conservative* harvest scenario, the productivity of the parcels follows the assumptions described in Figure 1, both before and after clearcutting and replanting.

The results of these simulations are described in Figures A2 and A3. In the *no harvest* scenario, the stock of carbon stored in dead and living biomass increases until 2125. However, with no harvest, the parcels successively reach the phase of declining carbon stock; cf. Figure 1. Hence, in the no harvest scenario, the considered area enters a phase of declining carbon stock during the first half of the next century (see the upper curve in Figure A2).

In the *conservative* harvest scenario, the rotation time varies around 90–110 years. Hence, the considered area does not enter a phase of declining carbon stock. Instead, the carbon stock of the considered area stabilizes at 64 MtC (see Figure A2).

In the *optimistic* harvest scenario, the carbon stock increases over the whole simulation period. This is because of the assumption that areas where clearcutting has taken place will experience 25 percent higher productivity than they had in the previous rotation period. Hence, as the parcels in the considered area are successively felled, they enter a phase with more rapid regrowth. In the middle of the 23rd century, the carbon stock becomes higher in the *optimistic* harvest scenario than in the *no harvest* scenario (see Figure A2).

Figure A2. Carbon stored in dead and living biomass in the area of 7000 km2 considered in section 6. In the two scenarios with harvest, it is assumed that both tops and branches are harvested together with the trunks



Again the question is how large volumes of CO_2 emissions from fossil energy can be eliminated by increasing the harvest. This is illustrated in Figure A3. The two straight lines in Figure A3 are identical to the straight lines in Figure 7 because we still consider the substitution effect of 3 Mm^3 wood (or 4.1 Mm^3 including tops and branches). Hence, the blue line in Figure A3 shows the reduced emissions from coal burning when pellets replace coal in power plants. Correspondingly, the red line in Figure A3 shows the reduced CO_2 emissions from combustion of fossil fuels due to increased supply of biofuels from wood.

A comparison of Figures A3 and 7 shows that the net effect of increased harvest does not change substantially when increased harvest is achieved through expanding the harvested area instead of reducing the average length of the rotation period. Expansion of the harvested area implies that the carbon debt is repaid somewhat later than was the case with reducing the length of the rotation period. In the *optimistic* scenario, as expected, the carbon debt is repaid sooner than in the conservative scenario. However, the carbon debt is still not repaid until some decades into the next century.

Figure A3. **The two straight lines show the achieved accumulated reductions in CO_2 emissions from the combustion of fossil fuels due to the increased supply of bioenergy. The curves show to what extent the forest's carbon stock is reduced as the harvest is increased, compared with the no harvest scenario. The extra timber harvested is used as energy and replaces fossil energy. It is assumed that both tops and branches are harvested together with the trunks**

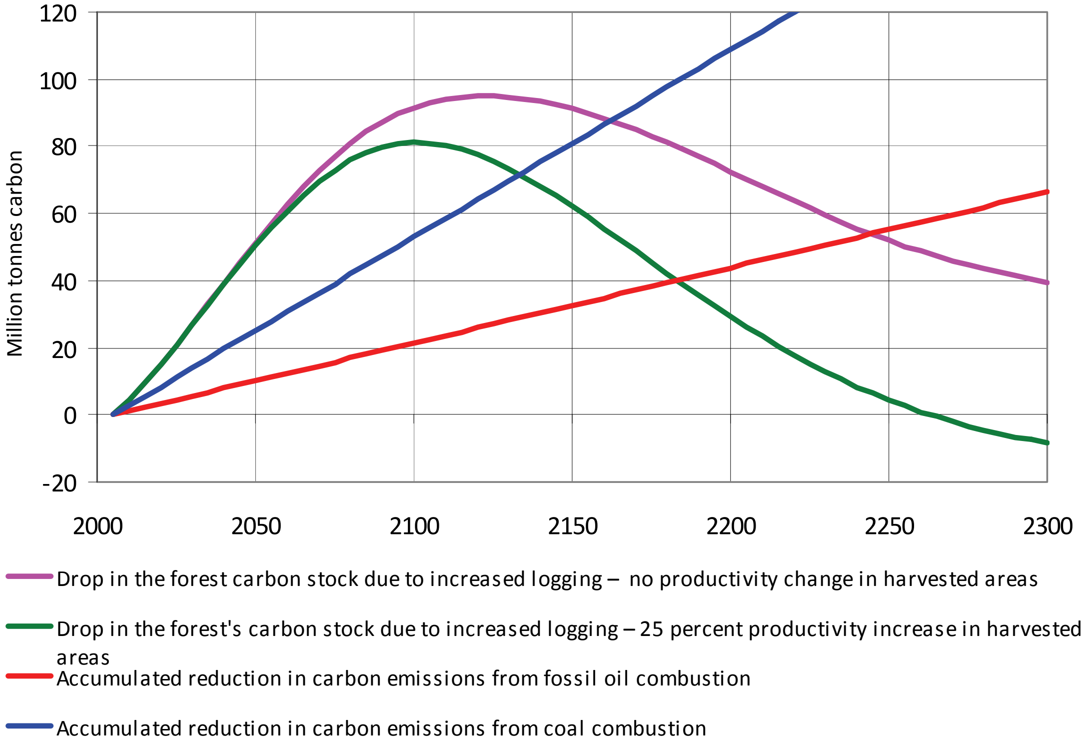


Table A1. **Time to repay the biofuel carbon debt from increased harvest in a boreal forest (years)**

	Increased harvest through reduced length of the rotation cycles	Increased harvest through extension of the harvested area – *conservative scenario**	Increased harvest through extension of the harvested area – *optimistic scenario*
Wood fuels replace pellets in coal-fired power plants	150	150	125
Second generation wood fuels replace fossil diesel	230	235	175

* The *optimistic* harvest scenario assumes that after clearcutting and replanting, the density of trees in the harvested parcels is 25 percent higher than the previous density of the standard parcels, as described in section 2, Figure 1.

A3. Expressions and parameter values used

In this section of the appendix, all expressions and parameter values are presented. This should enable the reader to reproduce all the results presented in the paper.

The forest contains P identical parcels, each covering an area of 1 km^2. Let S_t and S_{pt} be the volume of living trunks in the entire forest and in parcel number p, respectively. Hence, we have

(1) $$S_t = \sum_{p=1}^{P} S_{pt}.$$

The volume of standing trunks in a single standard parcel (S_{pt}) develops according to

(2) $$S_{pt} = \sum_{\tau=t_{pt}}^{t} \left(\sum_{i=1}^{3} g_i e^{x_{ip}(\tau)} \right) \text{m}^3, p = 1, \ldots, P,$$

where t_{pt} is the year of the last clearcutting and replanting of parcel p at time t, while g_i (i = 1, 2, 3) are parameters (see Table A2), and x_{ip} (τ) is defined as

(3) $$x_{ip}(\tau) := -\frac{\left(0.2(\tau - t_{pt}) - m_i\right)^2}{k_i}, i = 1,2,3, \ p = 1, \ldots, P,$$

where m_i and k_i are parameters (see Table A2). The trunks constitute a share s = 48 percent of the total living biomass at any point in time. Hence, the volume of other living biomass in a single parcel (U_{pt}) is

(4) $$U_{pt} = \frac{1-s}{s} S_{pt}, p = 1, \ldots, P.$$

The share of living trees d_{pt} in a single parcel with stand age t_{pt} that do not survive period t_{pt}, is

(5) $$d_{pt} = \sigma \frac{Ke^{rt_{pt}}}{K - 1 + e^{rt_{pt}}}, p = 1, \ldots, P,$$

where K, r and σ are parameters (see Table A2).

This means that a parcel p generates the following amount of natural deadwood in period t:

(6) $$\Delta_{pt} = d_{pt}\,(S_{pt} + U_{pt}), p = 1, \ldots, P.$$

It follows that the total amount of natural deadwood generated in period *t* is

$$(7) \qquad \Delta_t = \sum_{p=1}^{P} \Delta_{pt} \ .$$

The following expressions are applied to the rate of decomposition of deadwood:

$$(8) \qquad \alpha_{j\tau} = \begin{cases} 1 - \left(\dfrac{\tau}{100} \right)^{\delta_j} & if \ \tau < 100, j = N, F, \\ 0, \ if \ \tau \geq 100, & \end{cases}$$

where $\alpha_{N\tau}$ and $\alpha_{F\tau}$ are the shares of deadwood and harvest residues, respectively, that have not decomposed after τ years. Hence, the total volume of natural deadwood in period *t* is

$$(9) \qquad D_t = \sum_{\tau=0}^{100} \alpha_{N\tau} \Delta_{p\tau} .$$

The values of all parameters are given in Table A2.

Table A2 Parameter values

Parameter	Value	Parameter	Value	Parameter	Value
g_1	2550	k_1	70	s	0.48
g_2	–550	k_2	500	δ_{Nt}	0.57571
g_3	–1442	k_3	20	δ_{Ft}	0.43068
m_1	14	K	800	P	75000
m_2	38	r	0.053		
m_3	–7	σ	$6.5 \cdot 10^{-5}$		

The age structure of the wood in the starting year (2010; before felling) is given in Table A3.

Table A3. Age structure of the forest in the starting year

Stand age (years)	Share of area (percent)	Stand age (years)	Share of area (percent)	Stand age (years)	Share of area (percent)
0–5	1.3	50	3.5	95	5.7
10	1.5	55	3.8	100	5.7
15	1.7	60	4.1	105	5.8
20	1.9	65	4.4	110	5.7
25	2.1	70	4.6	115	5.6
30	2.3	75	4.9	120	5.5
35	2.6	80	5.2	>125	5.3
40	2.9	85	5.4		
45	3.2	90	5.5		

A4. Carbon and energy content of wood and substitution effects

The theoretical energy output of wood depends on both density and moisture content. Hohle (2001) recommends using the simple approximation

$$H = (5.32 - 6.02 \cdot x) \text{ kWh/kg},$$

where H is theoretical energy output and x is the moisture of the wood (percent). It is throughout assumed that 1 m^3 of dry wood has a mass of 423 kg, and that half of the mass is carbon. This gives 0.211 tonnes of carbon per m^3, or 0.774 tonnes of CO_2 per m^3 of wood used as fuel.

Sjølie and Solberg (2009) reported that pellets are 8 percent moisture and 92 percent dry wood.

With the assumed moisture content and density, 1 kg of wood represents $2.175 \cdot 10^{-3}$ m^3 of raw material. Hence, the energy output per cubic meter is

$$H = ((5.32 - 6.02 \cdot 0.08) / (2.175 \cdot 10^{-3})) \text{ kWh/m}^3.$$

However, Sjølie and Solberg (2009) also reported that the energy from 10 percent of the pellets produced has to be used to reduce the moisture content to 8 percent. In other words, 1.11 m^3 of wood is required to produce pellets with the same theoretical energy content as 1 m^3 of wood with a moisture content of 8 percent. Hence, the theoretical energy output from 1 m^3 of wood is

$$H = ((5.32 - 6.02 \cdot 0.08) / (2.175 \cdot 10^{-3})) \cdot (1/1.11) \text{ kWh/m3}.$$

With an assumed efficiency ratio of 35 percent, the final energy output per cubic meter of wood will be

$H_e = 0.35 \cdot ((5.32 - 6.02 \cdot 0.08) / (2.175 \cdot 10^{-3})) \cdot (1/1.11)$ kWh/m^3 = 700.8 kWh/m^3.

In other words, 1 m^3 of wood processed to pellets provides 700.8 kWh of energy when used for electricity production in a coal-fired power plant with 35 percent energy efficiency.

As regards fossil CO_2 emissions during processing, Sjølie and Solberg (2009) looked at two cases: one where they assumed that BioWood uses Norwegian hydropower, which does not generate CO_2 emissions, and one where they assumed that marginal power is imported and therefore mainly coal based. In practice, the truth probably lies somewhere between these two cases. I have therefore used the average of the two figures, which means that the emissions related to pellets processing are 224 tCO_2/GWh.

Based on the work of Weisser (2007), I have assumed that life-cycle CO_2 emissions from a coal-fired power plant with 35 percent efficiency total 931 tCO_2/GWh.[7] Subtracting fossil CO_2 emissions of 224 tCO_2/GWh from pellet production, we find that the net reduction in fossil CO_2 emissions is 707 tCO_2/GWh.

Taking into account that the energy output is 700.8 kWh/m^3, we find that using 1 m^3 of pellets instead of coal in a power plant can eliminate 0.496 tonnes of fossil CO_2 emissions.

A5. Sensitivity analysis

The determination of the speed of decomposition of deadwood is based on the work of Liski et al. (2005), and is a source of uncertainty in the calculations. I have therefore run a number of sensitivity simulations, which are presented below.

The share of natural deadwood that has decomposed after *t* years is given by expressions (5) and (6) above. To test the sensitivity of these assumptions, both higher and lower decomposition rates are

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[7] Based on the work of Hartmann and Kaltschmitt (1999), Sjølie and Solberg (2009) assumed that life-cycle emissions from a coal-fired power plant are 1167 tonnes CO_2/GWh. However, Hartmann and Kaltschmitt (1999) suggested this figure based on the assumption that the power plant's efficiency was 43.2 percent, while Sjølie and Solberg (2009) used the same figure when the power plant's efficiency is 35 percent. Because of this inconsistency, I have based my assumptions on the work of Weisser (2007).

considered in addition to the reference case (see Tables A4 and A5). The parameters *d* and *s* in the three cases are given in Table A2.

Table A4. Parameters δ_{Nt} and δ_{Ft} in the three cases considered

	δ_{Ft}	δ_{Nt}
High rate of decomposition	0.301	0.365
Reference case	0.431	0.576
Low rate of decomposition	0.756	1.000

Table A5. Time to repay the carbon debt if the wood is processed to pellets and replaces coal in power plants—different rates for the decomposition of deadwood*

		Time required for the decomposition of 50 percent of natural deadwood (years)		
		15	30	50
Time required for the decomposition of 50 percent of harvest residues (years)	10	140	160	170
	20	135	150	165
	40	130	140	155

* Only the case with increased period of the rotation cycle is considered.

Table A6. Time to repay the carbon debt if the wood is processed to second-generation liquid biofuels and replaces liquid fossil fuels—different rates for decomposition of deadwood

		Time required for the decomposition of 50 percent of natural deadwood (years)		
		15	30	50
Time required for the decomposition of 50 percent of harvest residues (years)	10	225	235	260
	20	220	230	255
	40	210	225	245

* Only the case with increased period of the rotation cycle is considered.

In the reference case, it follows that 50 percent of natural deadwood decomposes within 30 years, whereas it only takes 20 years for 50 percent of the harvest residues to decompose. It is assumed that natural deadwood decomposes more slowly than harvest residues because the former includes the long-lasting trunks.

In the case with the high rate of decomposition, it follows that 50 percent of natural deadwood and harvest residues have decomposed after 15 and 10 years, respectively. In the case with the low rate of decomposition, it follows that 50 percent of natural deadwood and harvest residues have decomposed after 50 and 40 years, respectively.

As is evident from Tables A4 and A5, the results are relatively insensitive to the assumed rate of decomposition of deadwood.