Supplemental Online Material for:

Harvesting in boreal forests and the biofuel carbon debt

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This supplemental online material provides initially a detailed model description with all the parameter values and a number of sensitivity simulations with regard to the decomposition rate of deadwood. Furthermore, it clarifies the importance of considering not only a single harvest event in the case where a permanently higher harvest level is to be analyzed, and presents two scenarios where a greater harvest can be achieved through expansion of the harvested area, rather than adjusting the rotation length, as considered in sections 3.2 and 3.3 in the article.

1 The model

1.1 The structure of the model

First, this section explains the structure of the model. Second, the chosen functional forms and parameter values are presented.

Borrowing a term from economics, the model could be considered as an "overlapping-generations" model of parcels with different stand ages. However, while the population size of an overlapping-generations model usually varies over time, the modeled forest contains a *fixed* set of parcels, I, with each parcel covering an area of 1 km^2. The number of parcels is labeled n. Essential for the dynamics of the model is that immediately after clear-cutting has taken place in a parcel, the parcel's volume of living biomass is zero and the growth path described in section 1.2 below restarts.

Let B_t and B_{it} be the volumes of living biomass in the entire forest and in parcel number i at time t, respectively. It follows that

$$B_t = \sum_{i \in I} B_{it}. \tag{1}$$

The volume of biomass in a single parcel depends solely on the time since last clear-cutting in that parcel (i.e., the parcel's stand age $\tau_i(t)$):

$$B_{it} = B(\tau_i(t)). \tag{2}$$

The function $B(\tau_i(t))$ is further described in section 1.2.

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Define A_t as the set of parcels where clear-cutting takes place at time *t*. Define *w* as the share of the biomass harvested. The harvested volume H_t at time *t* is then given by

$$H_t = w\sum_{i\in A_t} B_{it}. \tag{3}$$

The trunks are assumed to constitute *s* = 48 percent of the biomass of any parcel at any time. Hence, to the extent that *w* > *s* = 0.48, residues are also harvested.

It follows that the volume of harvest residues left in the forest at time *t* is

$$\Delta_{Ht} = \frac{1-w}{w} H_t. \tag{4}$$

Let $d(\tau)$ be the share of living biomass in a parcel with stand age τ that does not survive until the next period. The amount of natural deadwood that parcel *i* generates in period *t* is

$$\Delta_{Nit} = d(\tau_i(t))B(\tau_i(t)),\ i = 1,\ldots,n. \tag{5}$$

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

$$\Delta_{Nt} = \sum_{i\in I}\Delta_{Nit}\ . \tag{6}$$

Let $\alpha_N(\tau)$ and $\alpha_H(\tau)$ be the shares of natural deadwood and harvest residues, respectively, that have not decomposed after τ years. Assume that deadwood decomposes completely over a period of *T* years. Hence, while $\alpha_N(0)= \alpha_H(0)= 1$, we have that $\alpha_N(T)= \alpha_H(T)= 0$. It follows that the total accumulated volume of natural deadwood and harvest residues in the whole forest in period *t* is

$$D_{jt} = \sum_{\tau=0}^{T}\alpha_j(\tau)\Delta_{jt-\tau},\ j = N,H. \tag{7}$$

1.2 Functional forms and parameter values

Functional forms and parameter values are chosen to simulate as realistically as possible the different dynamic properties of the Norwegian forest. To have a path of the stock of living biomass corresponding to a Norwegian spruce forest of medium productivity (cf. Braastad (1975)), a set of functions are added as follows

$$B_{it} = \frac{1}{s}\sum_{\tau=0}^{\tau_i(t)}\left(\sum_{j=1}^{2} g_j e^{x_j(\tau)}\right),\ i = 1,\ldots,n, \tag{8}$$

where g_1 and g_2 are parameters. The functions $x_j(\tau)$ are defined as

$$x_j(\tau) = -\frac{\left(\frac{\tau}{5} - m_j\right)^2}{k_j},\ j = 1,2, \tag{9}$$

where m_j and k_j are parameters.

The share of living biomass $d(\tau_i(t))$ in parcel *i* that does not survive period *t* is

$$d(\tau_i(t)) = \sigma\frac{Ke^{r\tau_i(t)}}{K-1+e^{r\tau_i(t)}},\ i = 1,\ldots,\ n, \tag{10}$$

where K, r, and σ are parameters. The following expressions are applied to the rate of decomposition of deadwood.

$$\alpha_j(\tau) = \begin{cases} 1 - \left(\frac{\tau}{T}\right)^{\delta_j} & \text{if } \tau \le T,\ j = N, H, \\ 0, & \text{if } \tau > T. \end{cases} \tag{11}$$

The values of all parameters are given in Table S1.

Table S1 Parameter values

Parameter	Value	Parameter	Value	Parameter	Value
g_1	2550	k_1	50	s	0.48
g_2	–1442	k_2	20	δ_N	0.576
m_1	13.3	K	350	δ_F	0.431
m_2	–7	r	0.053	n	75000
σ	6.25 x 10^{-5}	T	100		

The age structure of the wood in the starting year (2010; before felling) is based on the work of Larsson and Hylen (2005) and given in Table S2. Given this age structure, the chosen functional forms and the parameter values, it follows that in the starting year, the total volume of living wood is 1583 Mm^3, containing 334 MtC. With the assumed initial stock of harvest residues (75 MtC) and natural deadwood (8 MtC), it follows that the forest's carbon stock (not including soil carbon) is 417 MtC in the starting year.

Table S2 Age structure of the forest in the starting year

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

1.3 Carbon and energy content of wood and substitution effects

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

$E = (5.32 - 6.02 \cdot y)$ kWh/kg,

where E is theoretical energy output and y is the moisture in the wood (percent). It is assumed throughout 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

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

However, Sjølie and Solberg (2009) also reported that 10 percent of the pellets produced have 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

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

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

$E_e = 0.35 \cdot ((5.32 - 6.02 \cdot 0.08) / (2.175 \cdot 10^{-3})) \cdot (1/1.11)$ kWh/m^3 = 701 kWh/m^3.

In other words, 1 m^3 of wood processed to pellets provides 701 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 pellet processing are 224 tCO_2/GWh.

On the basis of 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 under 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 was 35 percent. Because of this inconsistency, I have based my assumptions on the work of Weisser (2007), and assumed that life-cycle CO_2 emissions from a coal-fired power plant with 35 percent efficiency total 931 tCO_2/GWh. Subtracting fossil CO_2 emissions of 224 tCO_2/GWh from pellet production, I find that the net reduction in fossil CO_2 emissions is 707 tCO_2/GWh.

Taking into account that the energy output is 701 kWh/m^3, I 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.

1.4 Sensitivity analysis with regard to the decomposition rate of deadwood

On the basis of the work of Liski et al. (2005), it is assumed that deadwood decomposes at the rate shown in Figure S1. Natural dead biomass decomposes rather more slowly than harvest residues because natural deadwood also contains tree trunks, which break down 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 following, I present a number of sensitivity simulations with regard to these assumptions. The model simulations presented in sections 3.2 and 3.3 of the article are redone, now assuming different rates of decomposition.

Fig. S1 Remaining share of wood after natural death or clear-cutting. The symbols show the proportion of the wood that has not decomposed at the given time

The share of natural deadwood and harvest residues that has not decomposed after *t* years is given by equation (11). To test the sensitivity of the underlying assumptions, both higher and lower values of the parameters δ_F and δ_N are considered; see Table S3.

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 long-lasting trunks.

In the case of 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 of 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 S4 and S5, payback times are significantly lower if a high rate of decomposition of natural deadwood is combined with a low rate of decomposition of harvest residues. However, a case where natural deadwood decomposes more rapidly than harvest residues is unlikely (Storaunet and Rolstad 2002).

Table S3 Parameters δ_N and δ_F in the cases considered

	Years for the decomposition of 50 percent of residues	δ_F	Years for the decomposition of 50 percent of natural deadwood	δ_N
High rate of decomposition	10	0.301	15	0.365
Reference case	20	0.431	30	0.576
Low rate of decomposition	40	0.756	50	1.000

Table S4 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*

	Rate of decomposition of natural deadwood		
	High	Reference case	Low
High rate of decomposition of residues	185	195	215
Reference case (residues)	175	190	205
Low rate of decomposition of residues	160	170	190

Table S5 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

	Rate of decomposition of natural deadwood		
	High	Reference case	Low
High rate of decomposition of residues	335	355	385
Reference case (residues)	320	340	375
Low rate of decomposition of residues	295	315	350

2 Single-harvest analyses vs. multiple-harvest analyses

The Manomet Center for Conservation Sciences (2010) presented an analysis of the carbon debt generated by a single-harvest event and the corresponding payback time. In this section, it is demonstrated that the payback time determined from such a single-harvest analysis is much shorter than the payback time determined from analysis of a series of subsequent harvest events.

As an example, consider a forest with 19 parcels. All the parcels have the same size and dynamic properties as the standard parcel described in section 1.2 of this supplement and in section 2

of the article. Assume furthermore that parcel #1 was harvested in 1915 and that the forest owner, in a harvest scenario, sticks to a rotation period of 95 years. Consequently, this parcel was ready for harvest in 2010. Furthermore, parcel #2 was last harvested in 1920 and therefore matures in 2015, parcel #3 matures in 2020, and so forth. If the parcels are harvested at these points in time, they will again mature in 2105, 2110, 2115, and so forth, respectively.

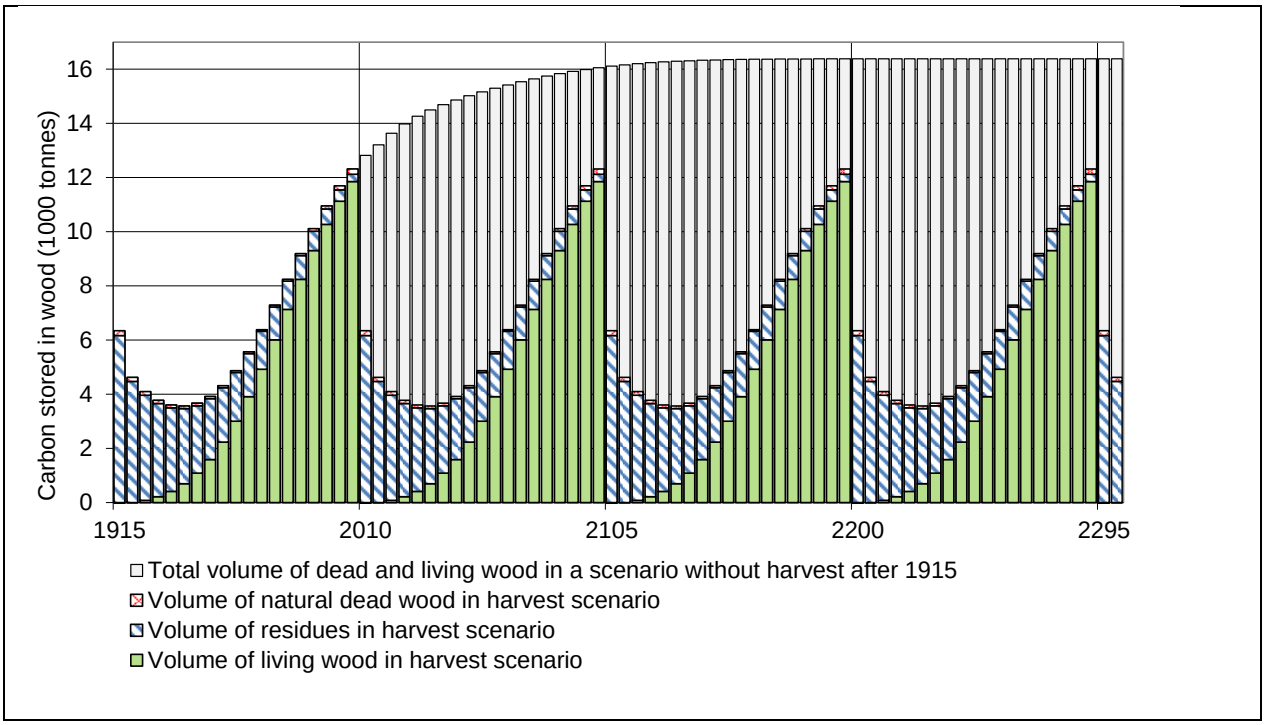

Fig. S2 The development of stock of carbon stored in dead and living wood in parcel #1, both in the case with clear-cutting in 2010, 2105, 2200, and 2295, and in that without harvest after 1915

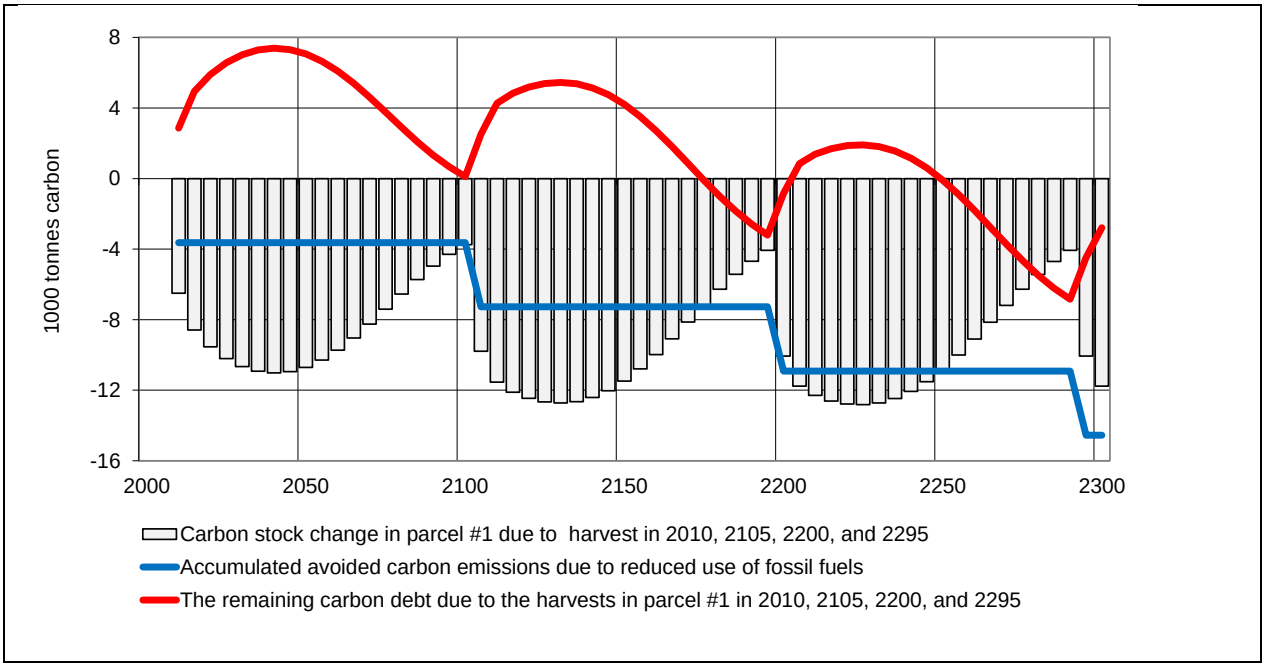

Fig. S3 Consequences of harvest in parcel #1 on this parcel's carbon stock, the accumulated reduction in fossil carbon emissions, and the remaining carbon debt

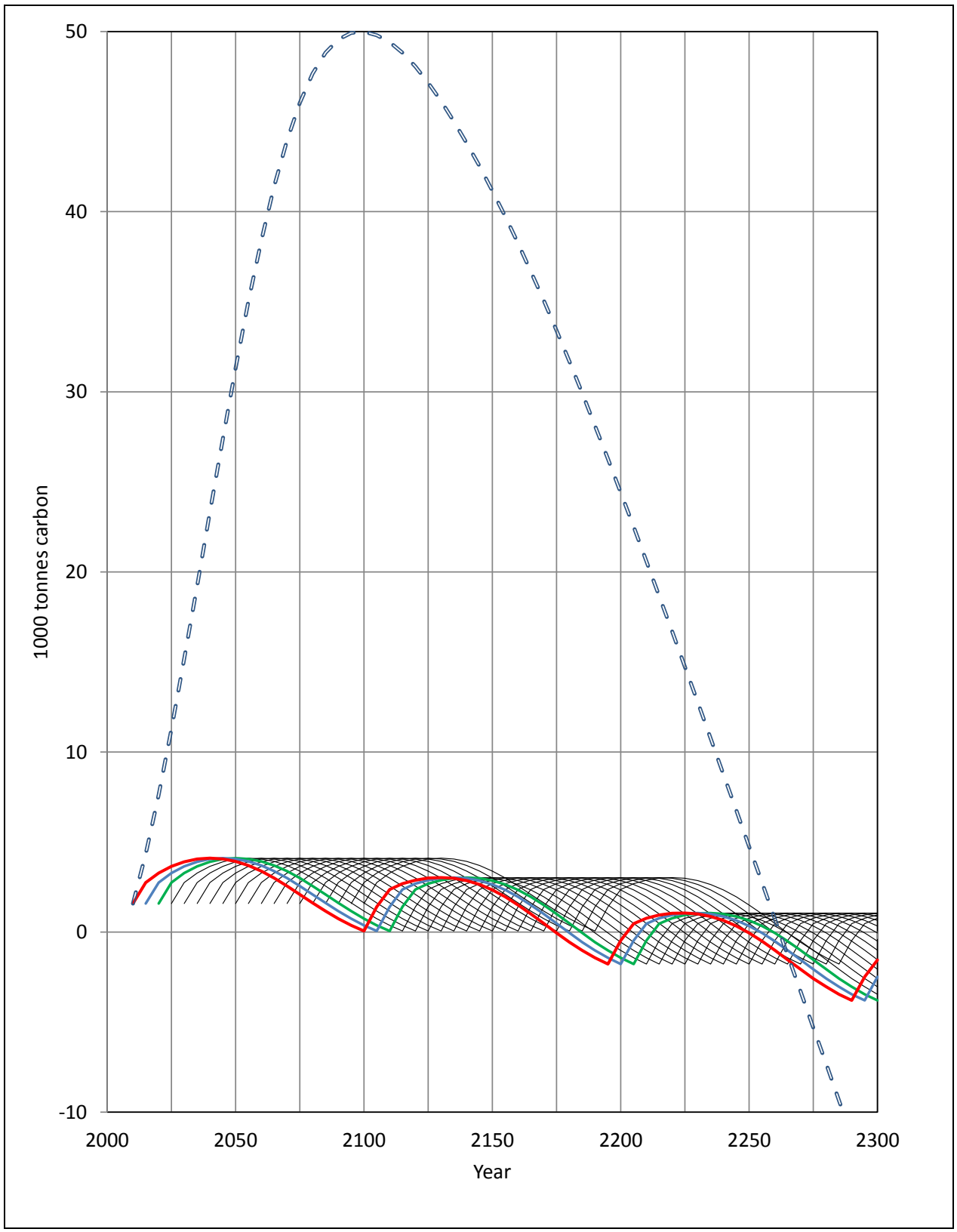

Fig. S4 The multi-wave-shaped curves show the development of the remaining carbon debt generated from the harvesting of 19 parcels as they subsequently mature. The total remaining carbon debt is given by the broken blue curve

Figure S2 shows the development of the volume of carbon stored in dead and living wood in parcel #1 in two cases. The colored columns show the case where clear-cutting and harvest of the trunks took place in 2010, and will also take place in 2105, 2200, and 2295. The gray columns, standing behind the colored columns, show the development if harvest does not take place after 1915.

It is evident from Figure S2 that harvesting means that less carbon is stored in the parcel. This drop in the parcel's carbon stock due to harvest is also illustrated with the gray columns in Figure S3. The lengths of the gray columns in Figure S3 are equal to the apparent parts of the gray columns in Figure S2.

For simplicity, it is in this example assumed there is no harvest of residues. However, it is assumed that each cubic meter of wood harvested means that 0.5 tonnes of fossil CO_2 emissions, or 0.14 tC, is avoided. Each parcel provides 26 900 m^3 of wood at each harvest. Hence, with the assumptions made, 3600 tonnes of carbon emissions are avoided for each harvest; see the blue line in Figure S3. The blue curve takes a new step down at the time of each harvest and measures the accumulated reduction in carbon emissions due to the harvests in parcel #1.

The remaining carbon debt from the harvests of parcel #1 is equal to the vertical distance between the blue line and the bottom of the gray columns in Figure S3; see the red curve. Note that the carbon debt of the single harvest event taking place in 2010 is fully repaid by 2105, that is, after 95 years.

Consider next Figure S4. The red curve from Figure S3 is reproduced here. Note, however, that the scale on the vertical axis is different. Moreover, Figure S4 shows the carbon debt of the harvest that will take place in the other parcels. For example, the blue curve represents the remaining carbon debt from harvesting of parcel #2. These harvest events take place in 2015, 2110, 2205, and 2300. The carbon debt of harvest taking place in 2015 is also repaid after 95 years, that is, by 2110. Correspondingly, the green curve in Figure S4 represents the remaining carbon debt from harvesting of parcel #3. In the same manner, all black curves represent the remaining carbon debt of corresponding subsequent harvesting of the other 16 parcels in the example forest.

These harvest events imply a permanent harvest level of 26 700 m^3 of wood every five years. The question is then at what point in time will the generated carbon debt of this harvest strategy be fully repaid? To calculate this, I sum (vertically) the remaining carbon debt described by all the 19 wave-shaped curves in Figure S4. This gives the broken blue curve in Figure S4, which thus represents the aggregate remaining carbon debt from the harvest of the entire example forest. Note that the carbon debt is repaid in 2260, that is, there is a payback time of 250 years in this permanent-harvest example compared with a payback time of 95 years in the single-harvest example. This difference underlines that single-harvest analysis does not provide complete answers regarding the consequences of increased harvest levels.

One may perhaps wonder why the payback time here is 250 years, while in the corresponding case studied in sections 3.2 and 3.3 in the article it was found to be 190 years. Recall, however, that in the example studied here, no residues were harvested. This explains the majority of the difference. Moreover, the example studied here compares a situation with no harvest in a certain area with a scenario with harvest in the same area. As will be illustrated in the next section, this also means a somewhat longer payback time.

3 Extending the area harvested

Sections 3.2 and 3.3 considered a case where the large-harvest scenario did not imply an extension of the area harvested. Instead, increased harvest was achieved through adjustments of the length of the rotation cycles. Figure S5 shows the stand age at the time of felling in the two scenarios. In both scenarios, the rotation period stabilizes at a relatively high age.

This section, 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.

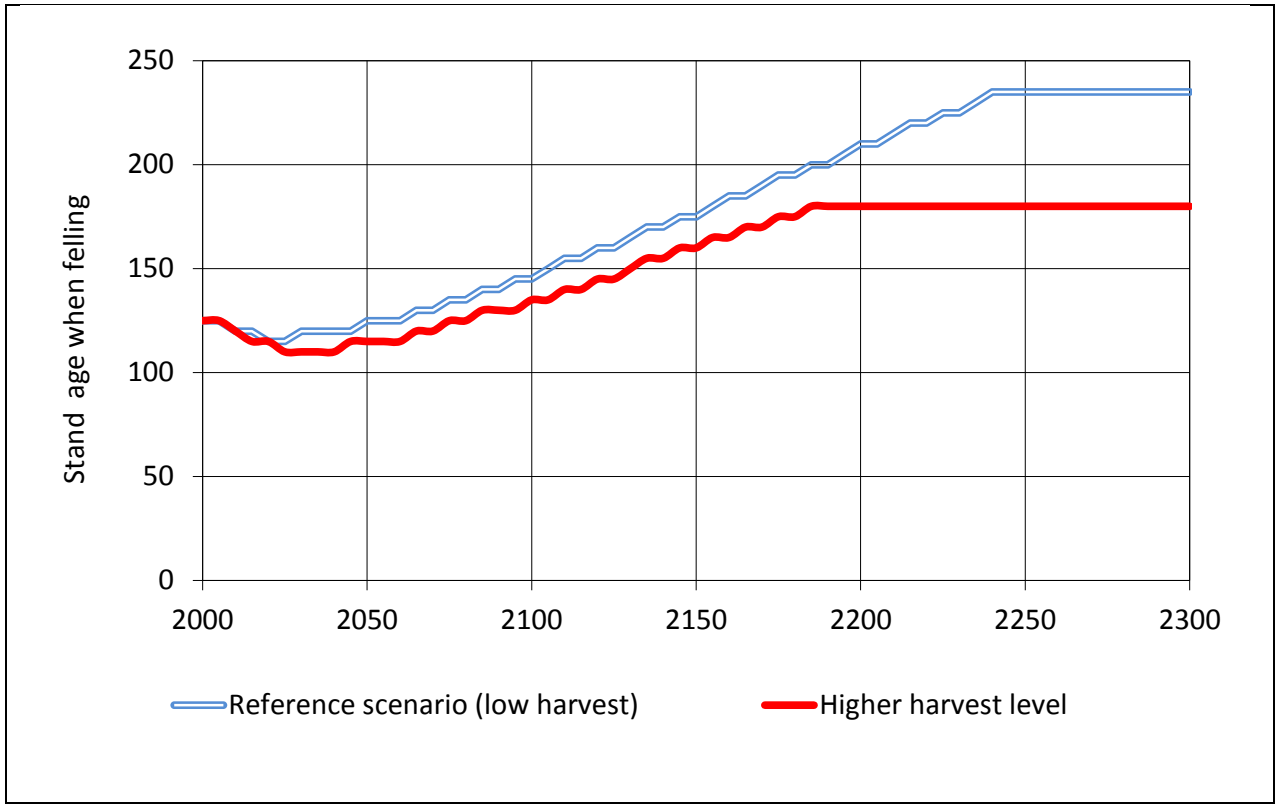

Fig. S5 Stand age at the time of felling in the two scenarios considered in sections 3.2 and 3.3

In the reference scenario, the harvest is 10 Mm^3, as in the case considered in sections 3.2 and 3.3. However, it is assumed that this harvest level is achieved through harvesting a limited area of only 45.5 percent or 34000 km^2 of the forest and a rotation period of 90–130 years. In the reference scenario, there is no harvest outside this area.

To increase the harvest from 10 to 13 Mm^3, an additional area of 10 108 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 Table S2.

In addition to the reference 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 is motivated by claims that harvest is an opportunity to replace sparse forests with more productive forests.

The *optimistic* harvest scenario assumes that after clear-cutting 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 S1. In other words, in the *optimistic* scenario, the stock of trunks and other living biomass in any parcel that has undergone clear-cutting and replanting in 2010 or later is 25 percent higher than would have been the case if the regeneration of the parcels had followed the path described in Figure 1. Hence, in the *optimistic* scenario, the development of the parcels' living biomass can be described as

$$B_{it} = \begin{cases} B(\tau_i(t)) \text{ if } \tau_i(t) > t - 2010, \\ (1+\varepsilon)B(\tau_i(t)) \text{ if } \tau_i(t) \leq t - 2010 \text{ and } t \geq 2010, \end{cases} \quad (12)$$

where the function $B(\tau_i(t))$ is described in equation (8) - (9) and it is assumed that the parameter $\varepsilon = 0.25$.

In the *conservative* harvest scenario, the productivity of the parcels follows the path described in Figure 1, both before and after clear-cutting and replanting. Said differently, the parameter $\varepsilon = 1$.

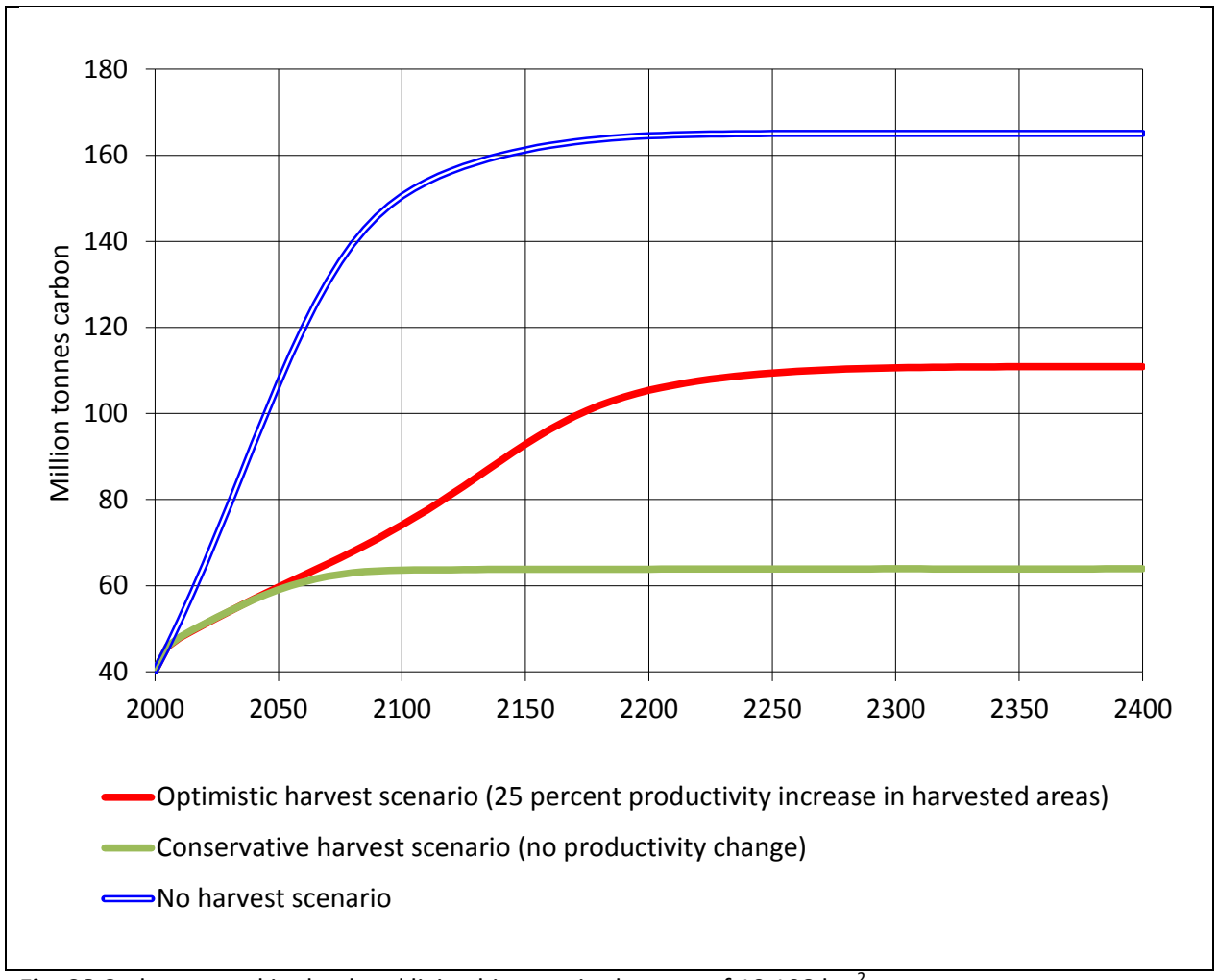

Fig. S6 Carbon stored in dead and living biomass in the area of 10 108 km^2

The results of these simulations are described in Figures S6 and S7. In the *no harvest* scenario, the stock of carbon stored in dead and living biomass increases until approximately the year 2200. The stock then stabilizes, i.e., a new steady state is reached.

In the *conservative* harvest scenario, the stock of biomass stabilizes at a lower level; see Figure S6. In the *optimistic* harvest scenario, the stock of biomass stabilizes at a higher level than in the conservative scenario. This is because of the assumption that areas where clear-cutting 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 and stabilization at a higher level.

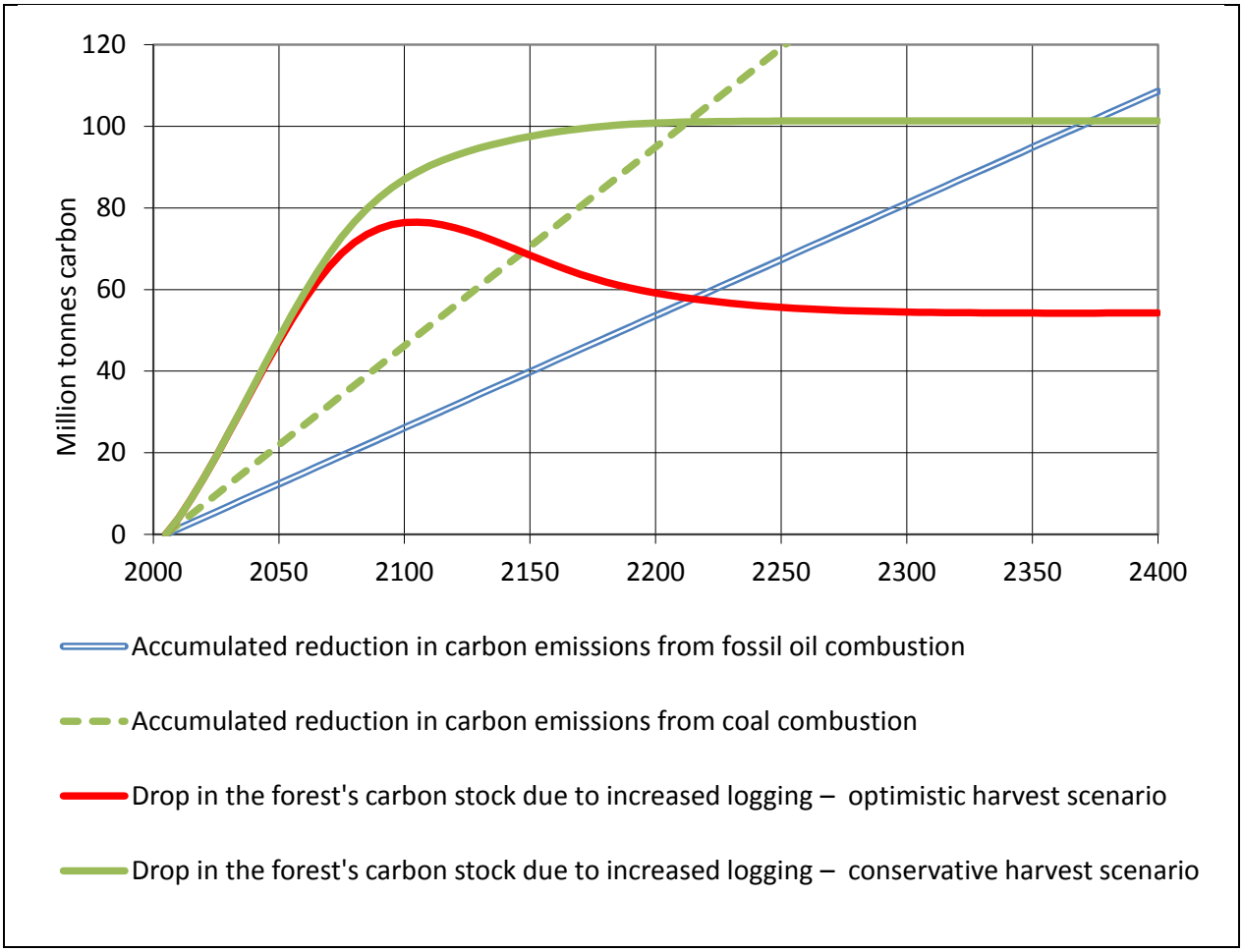

Fig. S7 The two straight lines show the accumulated reductions in CO_2 emissions achieved from the reduced combustion of fossil fuels due to the increased supply of bioenergy. The curves show to what extent the forest's carbon stock is reduced as the harvest is increased.

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 S7. The two straight lines are identical to the straight lines in Figure 4 in the article because we still consider the substitution effect of 3 Mm^3 of wood (or 3.6 Mm^3 including residues). Hence, the green broken line in Figure S7 shows the reduced emissions from coal burning (accumulated) when pellets replace coal in power plants. Correspondingly, the double line in Figure S7 shows the reduced CO_2 emissions from combustion of liquid fossil fuels (accumulated) due to increased supply of liquid biofuels from wood.

A comparison of Figures S7 and 4 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 when reducing the length of the rotation period. In the *optimistic* scenario, as expected, the carbon debt is repaid sooner than in the *conservative* scenario. Table S6 provides a summary of the calculated payback times.

Table S6 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	190	205	135
Second-generation wood fuels replace fossil diesel	340	360	205

* The *optimistic* harvest scenario assumes that after clear-cutting and replanting, the density of trees in the harvested parcels is 25 percent higher than the previous density of the standard parcels. See details in the text.

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