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Abstract:
Extensive tree planting on new areas has been suggested as a climate policy measure in Norway. This paper presents some preliminary calculations related to carbon dynamics of such a measure when the tree planting takes place on areas with relative young birch forests. The main finding, which is robust to several sensitivity analyses, is that after the tree planting project has been initiated, there will be a period of approximately 25 - 30 years with increased accumulation of CO_2 in the atmosphere. The reason is that clear cutting of existing vegetation and treeplanting initially will give a significant pulse emission. However, after that initial period with increased accumulation of CO_2 in the atmosphere, the project will lead to reduced accumulaiton of CO_2, due to the growth of the new trees and the corresponding carbon capture. This is also a robust result.

Keywords: Tree planting, Birch, Spruce, climate, carbon

JEL classification: Q23, Q42, Q54

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Sammendrag

Omfattende treplanting på nye områder har blitt foreslått som et klimapolitisk tiltak i Norge. Dette notatet presenterer noen foreløpige beregninger knyttet til karbondynamikken i et slikt tiltak når treplanting foregår på områder med relativ ung bjørkeskog. Hovedfunnet, som er robust overfor flere sensitivitetsanalyser, er at etter at treplantingsprosjektet er igangsatt, vil det være en periode på ca 25 - 30 år med økt mengde CO_2 i atmosfæren. Årsaken er at flatehogst av eksisterende vegetasjon og treplanting i utgangspunktet vil gi et betydelig utslipp. Imidlertid, etter at den første perioden med økt akkumulering av CO_2 i atmosfæren, vil prosjektet føre til redusert mengde CO_2 i atmosfæren på grunn av veksten av nye trær og den korresponderende carbon fangst. Også dette er et robust resultat.

Introduction

In order to increase CO_2 sequestration from forests, extensive planting of trees on new areas has been suggested as a climate policy measure in Norway (St. Meld. 21 2011-2012). Tree planting of 50 000 da/year at a total cost of approximately 100 million NOK per year over 20 years is for example mentioned as an option by Haugland et al. (2013). They concluded that it should be possible to find approximately 2000 hectares of non-forested areas or areas with less developed forests on unmaintained grassland that are suitable for planting of spruce trees leading to significant carbon sequestration. These areas include open grasslands and other cultural landscapes as well as pastures that have not been in use for a long time and therefore are partly forested with relatively young trees.

There has been some scepticism towards tree planting on these areas as a tool for carbon sequestration, see for example Saure (2014), who argues that albedo together with release of carbon related to harvesting will mean that the climate effect will not be as concluded by Haugland et al. (2013). This disagreement makes it valuable to look further at the issue.

In this paper I model the carbon sequestration generated if plans are realized as suggested by Haugland et al. (2013). I will focus especially on areas that have not been used as pastures for some years and now are forested with young birch trees. The existing young vegetation is removed and new trees are planted on the areas. I have adopted the suggestion in Haugland et al. (2013) where the tree planting project lasts for 20 years, which here implies that a new stand is clear cut every year during this period.

The basic method applied includes construction of a model of tree growth and carbon sequestration in the type of forest that will be generated through this government initiative. I estimate the size and the dynamics of the carbon debt (Fargione et al. 2008) that will be generated when trees are felled in order to give place for spruce trees. However, the carbon sequestration achieved through tree planting has to be evaluated against the carbon sequestration that could have taken place if the considered areas would not be subject to clear-cutting and planting. Hence, the paper also builds on reference scenarios without tree planting.

It should be emphasized that the present paper does not provide a complete picture of all environmental and climatic effects of tree planting in new areas, but considers the carbon dynamics only. This is only a first step in an evaluation of the climatic effects. A complete evaluation should take into account that tree planting will change the albedo. Furthermore, there is a lack of knowledge related to how tree planting will influence the dynamics of soil carbon. Taking such elements into account in full details could change the picture provided by the present paper. Moreover, there are other environmental aspects of tree planting on the mentioned areas, not least related to biodiversity which is not considered in the present paper. Hence, the calculations of this paper, saying that tree planting after a few decades could give climate benefits, should not be over-interpreted. A more detailed model along the lines mentioned, could lead to very different conclusions.

Materials and methods

The model

When analyzing tree planting, a large number of possible cases could be studied. This paper considers two only. In case 1 a stand with productivity index of 14 is considered, while in case 2 the stand's productivity index is 20 (Braastad 1975). A productivity index of 14 represent the most common forest productivity in Norway, while productivity index 20 represents significantly more productive areas that are somewhat less common in Norway.

In both cases, the assumed stand at the point of departure ($t = 0$) has 30 years old birch trees with productivity indexes of 14 and 20, respectively. With regard to the the *harvesting and tree planting* scenarios, it is assumed that clear cutting then takes place at time $t = 0$, and that Norway Spruce trees are planted on the stand, again considering both productivity levels mentioned. Furthermore, it is assumed that the spruce trees are harvested regularly with a rotation assumed to be 70 years. Sensitivity analyses are in addition carried out to see the effect of a scenario where the new trees are not harvested. In all cases, the tree planting scenarios are evaluated against a reference scenario where the stand is not harvested in the first place, hence, against a reference case where the growth of the birch forest instead continues.

Figures 1 - 4 give overviews of the properties of the stands considered. First, consider case 1 and the scenario without harvesting and tree planting (Figure 1). At time $t = 0$, assuming that harvesting has not yet taken place, the stand's total carbon stock is 108.1 tC, including 44.3 tC stored in living biomass, 3.9 tC stored in natural deadwood and 60 tC stored in the soil layer. In the tree planting scenario (Figure 2), stems of living trees together with 25 per cent of other living biomass (residues) are removed after clear cutting of the stand at time $t = 0$. Throughout it is assumed that stems constitute 48 per cent of total living biomass. This means that 27.0 tC is removed from that stand with subsequent combustion giving rise to a corresponding pulse of carbon. It follows that after clear-cutting and harvesting the stand stores 77.2 tC (Figure 2).

After clear cutting and harvesting, new trees are planted and start growing. Residues left on the forest floor decompose. Moreover, natural dead organic matter (NDOM) that was present on the stand at the time of harvesting also gradually decomposes, while new naturally dead biomass is slowly generated; see the dotted area in Figure 2.

With regard to the dynamics of the soil's carbon pool, it was assumed that clear cutting and replanting results in some years with a net release of carbon from the soil. Thereafter, the soil's carbon pool gradually returns to its original state; see Figure 2. As mentioned in the introduction, this is an uncertain part of the calculations that should be the subject for further research.

There is also great uncertainty about the likely development of the carbon stock of an old stand (Helin et al. 2013). However, in accordance with, e.g., Luyssaert et al. (2008), I assumed continued accumulation of carbon even in old stands. If older stands accumulate less carbon than I assume, three planting could be more attractive than found.

To calculate the net effect of clear-cutting the 30 year old stand and the planting of Norway Spruce, I compare the time profiles of the total carbon stocks of the considered stands in the tree planting scenario (Figure 2) and a in a reference scenario (Figure 1). The net flux of CO_2 between the stand and the atmosphere is calculated for both these scenarios. This exercise is made in both cases 1 and 2.

A detailed description of the numerical models follows below. The basic building blocks of the models are the following growth functions for living biomass on the stands:

$$L_{B14}(\tau) = a_{B12} e^{b_{B14}/\tau}, \tag{1}$$

$$L_{B20}(\tau) = a_{B20} e^{b_{B20}/\tau}, \tag{2}$$

$$L_{G14}(\tau) = a_{G14} e^{b_{G14}/\tau}, \tag{3}$$

$$L_{G20}(\tau) = \frac{a_{G20}}{1 + e^{b_{G20} - c_{G20}\tau}}, \tag{4}$$

where $L_j(\tau)$, $j = B14$, $B20$, $G14$, $G20$, are the amount of living biomass of birch and spruce stands, respectively, with productivity indexes j and stand ages τ. The indexes $B14$, $B20$, $G14$, and $G20$ represent birch (B) and spruce (G) with productivity indexes 14 and 20, respectively, while a_x, b_x, and c_x are parameters. The functional forms and parameter values are taken from Haugland et al. (2013). All parameter values are listed in Table 1.

In all considered cases the starting point is that, at time $t = 0$, the stand age is 30 years. In the tree planting cases, harvesting takes place at time $t = 0$, and regrowth restarts along the path described by $L_i(\tau)$, $i = G14$ or $G20$, although there will be new harvesting at time $t = 70$, 140, 210, and so forth (rotation length 70 years was assumed in both cases). In the reference cases there are no harvesting or replanting and the forest growth continues along the path described by $L_i(\tau)$ as defined in (1)-(2).

Trunks, with volumes $V_i(\cdot)$, are assumed to constitute a proportion $\theta = 0.48$ of total living biomass $L_i(\cdot)$ (Løken et al. 2012). It follows that

$$V_i(\cdot) = \theta L_i(\cdot), \; i = B14, G14, B20, \text{ and } G20.$$

Next, consider the dynamics of the pool of harvest residues. At the time of harvesting, the stock of stems, $V_{Bj}(\tau)$, $j = 14$, 20, is removed from the stand. In addition, a share σ of the residues is harvested. Hence, the total harvest is

$$E(\tau_h, \sigma) = V_{Bj}(\tau_h) + \sigma (L_{Bj}(\tau_h) - V_{Bj}(\tau_h)), \tag{5}$$

where the stand age τ_h at time of harvesting is assumed to be 30 years when the first harvest takes place, while the stand age is 70 years at the point of time of later harvestings. It will also be assumed that the entire harvested biomass is used as energy. Hence, in the harvest scenario, there will at time $t = 0$ be a pulse emission equal to $E(\tau_h, \sigma)$.

It is assumed that the entire harvested biomass is used for energy purposes immediately after harvesting. This means that a certain amount of fossil energy is not used. Hence, from the increased emissions caused by combustion of the biomass, it should be subtracted an amount of fossil emissions that then does not take place:

$$F(\eta, E(\tau_h, \sigma)) = \eta E(\tau_h, \sigma)$$

where η is a substitution parameter. It follows that at time of harvesting, there will be a net emissions pulse equal to $(1-\eta) E(\tau_h, \sigma)$. The size of the parameter η depends on a large number of factors, as type of bioenergy replaced (oil or coal, for example). Holtsmark (2012) explored two cases and found that if the biomass is converted to pellets and replaces coal in power plants, η is found to be 0.71. However, if the biomass is converted to liquid biofuels as biodiesel or bioethanol, the parameter η was found to be 0.4. In this paper the latter case has been chosen as the main case. Hence, the parameter η is set to 0.4. However, sensitivity analyses will be presented where the pellets/coal case ($\eta = 0.71$) is instead studied.

In the harvest case, an amount of residues, $(1-\sigma)(L(\tau_h) - V(\tau_h))$, is generated at time $t = 0$, while there are no harvest residues in the reference scenario. Hence, in the harvest scenario there is an amount of residues on the forest floor as described by the function:

$$D_R(t, \tau_h, \sigma) = e^{-t\omega}(1-\sigma)(L(\tau_h) - V(\tau_h)), \tag{6}$$

where ω is the annual decomposition rate for dead organic matter. Based on the results and the discussion in Liski et al. (2005), ω was set to 0.04. As it is known that decomposition rates differ greatly between different components of the trees, it would have improved the model to let the speed and time profile of decomposition depend on the type of residues and NDOM components (Repo et al. 2011). However, as discussed in Holtsmark (2012), the results are relatively insensitive to the size of this parameter.

Let subscript P refer to the tree planting scenario whereas subscript 0 refers to the reference scenario without harvesting and tree planting. Consider the pool of natural deadwood, $D_{Ni}(t)$, $i = P, 0$. The NDOM pool develops as follows:

$$D_{Ni}(t) = e^{-t\omega} D_{0i} + \frac{\phi_j k e^{\rho_i \tau}}{k + v(e^{\rho\tau} - 1)}, \quad i = P, 0, \text{ and } j = B14, B20, G14, G20, \tag{7}$$

where D_{0i} represents the amount of all dead organic matter (DOM) on the stand at time $t = 0$. Thus, the first term on the right-hand side represents the amount of DOM that remains from the previous rotations, and the second term on the right-hand side represents NDOM generated after time $t = 0$. Note that ϕ_j, k, and ρ are parameters. The parameter values were calibrated so as to give time profiles of the amount of NDOM that correspond to empirical knowledge, see discussion in Holtsmark (2012). Note that DOM is the sum of natural dead organic matter (NDOM) and harvest residues.

An important question is the extent to which harvesting and planting of new trees trigger release of soil carbon. As emphasized by Fontaine et al. (2007), Friedland and Gillingham (2010), Jonker et al. (2014), and Kjønaas et al. (2000), accumulation and release of carbon from the soil are complicated processes and there is a high degree of uncertainty at this point. However, according to field experiments reported by Olsson et al. (1996), the loss of carbon after clear-cutting in a spruce forest could be substantial. Olsson et al. (1996) found that 15 years after clear-cutting, the net loss of soil carbon from a spruce site is within the range 9 - 15 tC/ha. They found that in mature forests most of the soil carbon has been recaptured.

Based on Holtsmark (2015a,b), the following model of soil carbon was therefore applied:

$$M_i(t) = M_0 - (1 - \delta_i)\, m_1 e^{m_2 t} \left(1 - e^{m_2 t}\right)^{m_3}, \ i = P, 0,$$

where M_0 is the constant amount of soil carbon in the stand in the reference scenario, whereas m_1, m_2, and m_3 are parameters. They were calibrated to give a maximum soil carbon loss of 12 tC/ha 15 years after harvesting and tree planting. After 15 years, the stand's soil carbon pool was assumed to gradually increase back to its original state, see Figures 3 and 4. Although not important for this analysis, the fixed reference stock of soil carbon, M_0, was set to 60 tC/ha. This corresponds to a mean of the estimates of the amount of carbon contained in the organic part of the soil found by de Wit and Kvindesland (1999).

It should be noted here that it was assumed that forest residue removal does not amplify the loss of soil carbon after harvest and does not reduce future growth. This is probably somewhat optimistic (Johnson and Curtis, 2001).

The stand's total carbon stock, labeled $\Omega_i(t)$, includes the carbon pool of all living biomass $L(t)$, the pool of harvest residues $D_R(t)$, the NDOM pool $D_{Ni}(t)$ and soil carbon $M_i(t)$:

$$\Omega_i(t) = L(\delta_i \tau_h + t) + (1 - \delta_i)\, D_R(t) + D_{Ni}(t) + M_i(t), \ i = P, 0. \tag{8}$$

To sum up, in the clear-cutting and tree planting scenario, there will be a pulse emission $(1 - \eta)\, E(\tau_h, \sigma)$ at time $t = 0$, followed by a phase of regrowth and carbon capture, leading to a net flux from the stand to the atmosphere following the path $-\Omega'_P(t)$, $t \in (0, \infty)$. In the reference scenario, there will be no pulse emission at $t = 0$, but continued growth will lead to a negative net flux following the path of $-\Omega'_0(t)$, $t \in (0, \infty)$. All parameter values are listed in Table 1. $\Omega'_i(t)$ represents the time derivative of $\Omega_i(t)$, which is the net carbon flux from the atmosphere to the stand due to the stand's growth as well as the release of soil carbon and the release of CO_2 from the decomposition of harvest residues and NDOM.

Accumulation of carbon in the atmosphere

The following function was used to calculate the fraction $y(t)$ of an initial pulse of CO_2 at time $t = 0$ that remains in the atmosphere at time t:

$$y(t) = y_0 + \sum_{i=1}^{3} y_i e^{-t/\alpha_i}, \qquad (9)$$

where α_i and y_i are parameters. This decay function is based on Joos and Brune (1996), and Joos et al. (1996, 2001), labeled the Bern 2.5 CC carbon cycle model. It is supposed to take into account how a pulse of CO_2 leads to increased absorption of CO_2 by the terrestrial biosphere and the sea. This carbon cycle model was also applied to fluxes of CO_2 generated by the stand's growth, as well as the release of CO_2 due to decomposition of NDOM and harvest residues left on the forest floor; see further details below. The profile of the function described is shown in Figure 5.

Let $A_P(t)$ be the amount of atmospheric carbon at time t that is caused by the harvest with subsequent combustion of the biomass and the stand's regrowth, while $A_0(t)$ is the amount of atmospheric carbon in the reference scenario, i.e., taking continued growth into account. We then have:

$$A_P(t) = (1-\eta) E(\tau_h, \sigma) \cdot y(t) - \int_0^t \Omega_P'(x) y(t-x) dx, \qquad (10)$$

$$A_0(t) = -\int_0^t \Omega_0'(x) y(t-x) dx, \qquad (11)$$

where $(1-\eta) E(\tau_h, \sigma)$ represents the pulse emission at time $t = 0$. In mathematical terms it is here carried out a convolution between the functions describing the net flux of emissions and the decay function described by (9).

The net effect on atmospheric carbon of harvesting compared to the reference scenario without harvesting is:

$$A(t) = A_P(t) - A_0(t). \qquad (12)$$

Simulation results

As should be evident from the previous section, the calculations presented in this paper have different "steps". In the first step, the time profiles of a single stand's carbon stocks in both the reference case and the harvesting and tree planting case are calculated, see the dotted curves and the solid, blue curves in Figures 6 and 7. Subtracting vertically the dotted curve from the blue curve in both these figures, gives the broken, green curves, representing the net effect on the stand's carbon stock of harvesting and tree planting. As harvesting and tree planting cases will give some amounts of biomass used for bioenergy, the amounts of replaced fossil fuels emissions are accounted for in the second step. How these avoided emissions accumulate over time is shown by the yellow lines in Figures 6 and 7. By vertically subtracting the yellow line from the dashed green line in the two Figures, respectively, the result will be the double-lined red curves in Figures 6, 7, 8 and 9. These curves give the net effects on accumulated carbon emissions, and show that with both productivity cases, there will be a period of approximately 25 years after harvesting where the accumulated emissions will be increased. Subsequently accumulated emissions will be reduced. However, after that time period, the harvesting and tree planting case leads to a reduced level of atmospheric carbon.

The third step is to calculate how these accumulated emissions influence the content of carbon in the atmosphere, taking the atmospheric lifetime of CO_2 into account. At this step, the Bern 2.5CC carbon cycle model was applied in combination with the models of the carbon pulses and fluxes, as described by equations (10) and (11). These operations give final effect on atmospheric carbon, see the blue curves of Figures 8 and 9. This calculation step changes the picture somewhat, although not fundamentally. The period with increased accumulation of carbon in the atmosphere is still approximately 25 years. However, the blue curves in Figures 8 and 9 show that there is found to be periods around 70 - 90 years after harvesting and tree planting where the project leads to higher atmospheric CO2. In the low productivity case, there is found to be a short period with higher atmospheric CO2 level also approximately 150 years after harvesting.

The final step in the calculations is to go beyond the single stand approach and take into account that the tree planting project is supposed to last for a number of years. The proposal by Haugland et al. (2013) is to start harvesting and tree planting projects every year over a period of 20 years. Therefore, it was here assumed that a new stand every year over a 20 year period is harvested and is replanted.

The red curves of Figures 10 and 11 are exactly the same as the blue curves of Figures 8 and 9, respectively. The other curves that run parallel to the red curves represent the corresponding effects of the clearcutting and harvesting of the 19 other stands included in the project. For example, the blue curves of Figures 10 and 11 are the corresponding effects of a harvesting and replanting project in the subsequent year. The other thin curves of Figures 10 and 11 represent the effects on atmospheric carbon of harvesting and tree planting on another new stand for each of the subsequent 18 years, respectively.

To find the net effect on atmospheric carbon of the entire 20-years tree planting project, alle the thin curves of Figures 10 and 11 should be added vertically. This operation leads to the thick black curves of Figures 10 and 11. Note that the thick black curves are measured along the right axes (with a different scale compared to the left vertical axis) and show the net effect on atmospheric carbon of the entire 20 years harvesting and tree planting project, for the two productivity cases considered.

Note that the thick black curves to begin with are above the the horizontal axis before they cross approximately 30 years after project start. Hence, the tree planting project will increase the amount of carbon in the atmosphere for approximately 30 years after which there will be a reduction of atmospheric carbon. In the case with relatively slow growing trees (productivity index 14 for both birch and spruce), there will also be a period approximately 90 - 110 years after project start when there will be increased atmospheric carbon, see Figure 10. This is because the considered stands they are harvested and create an additional carbon debt. Also in when considered stands are more productive (index 20), there will be a second period with enhanced CO_2 level in the atmosphere. However, in this case it is very short and only slightly above the horizontal axis.

Sensitivity analyses

As mentioned, a number of sensitivity analyses were carried out. First, it was checked what would be the consequences of a case where the substitution factor for bioenergy against fossil energy as in a case where the biomass is processed to pellets and replaces coal in power plants. This case was considered in Holtsmark (2012) where it is argued that the substitution parameter η then should be 0.71. This parameter value was here adopted and thus replaced its original value $\eta = 0.40$.

The results are shown by Figures 12 and 13. The results do not change very much compared to the main case, where it was assumed that the biomass was processed to liquid biofuels and replaces oil. The length of the initial period with enhanced atmospheric CO_2 is reduced with a couple of years only. The effect is more significant with regard to the second period with enhanced atmospheric CO_2 in the low productivity case, see Figures 10 and 11. With the higher substitution factor the second period with enhanced atmospheric CO_2 now simply disappears, see Figures 12 and 13. The explanation here is that harvesting the spruce forest, gives more bioenergy than the initial harvesting. Hence, now the substitution factor plays a more important role.

A further sensitivity analysis was carried out to see the consequence of harvesting the new trees. An alternative could be not to harvest the considered stand after the first harvesting and instead let the new spruce forest be a permanent carbon storage. Figures 14 and 15 show the consequences of that scenario, where the more optimistic substitution factor from Holtsmark (2012) ($\eta = 0.71$) again was adopted.

The final sensitivity analysis carried out was to reduce the stand age of the original birch stand from 30 to 10 years, while the substitution is still optimistic ($\eta = 0.71$). The effects on soil carbon were not changed. Figures 16 and 17 show the time profiles of the different variables in this case. Note for example that because a 10 year old birch stand will give a limited harvest, the avoided fossil CO_2 emissions at time $t = 0$ will also be limited. Nevertheless, also in this case there will be a period close to 25 years long with enhanced atmospheric CO_2 levels in the single stand case. Figures 18 and 19 show the results of the multi stand simulations, showing that the the main findings with regard to the initial period with enhanced accumulation of atmospheric CO_2 is relatively robust against these type of assumptions.

Discussion and conclusion

There are a number of important findings from the simulations described in the previous section.

First, harvesting relatively young birch stands and planting of spruce trees on the same stands will lead to less accumulation of carbon in the atmosphere in the long term, at least if the harvested biomass is used to replace fossil fuels. This result is quite robust to changes of assumptions made.

Second, there will be a period with enhanced atmospheric CO_2 level of approximately 30 years. Also this result is relatively robust to assumptions made.

Simulations were carried out with less optimistic assumptions with regard to the amount of fossil CO_2 emissions that could be replaced. Moreover, simulations were carried out assuming a lower stand age of the original birch stand. Even with these two assumptions in combination, the length of the period with enhanced CO_2 level did not change very much. This is noteworthy, as it could appear obvious that a significantly younger birch stand, storing significantly less carbon, would mean a correspondingly shorter period with enhanced atmospheric CO_2 level.

A third finding was that if the spruce trees are harvested, that could lead to another period with enhanced CO_2 level approximately 70 - 100 years after the start of the project. However, this result is less robust.With more optimistic assumptions with regard to the substitution factor against fossil fuel, this result is no longer is valid.

Although the main results of the paper are robust with regard to the mentioned parameter choices, it should be emphasized that important factors are not included in the model. The present paper considers only carbon and CO_2, although there are many studies that emphasize that the net effect of forest management depends on a number of other factors also, see for example Naudts et al. (2016). One factor here is how different types of forest influence aerosols. Another important factor ignored in the present paper is for example albedo. A switch from birch to spruce will lead to a darker forest that might provide less albedo. There is, however, a considerable uncertainty at this point, especially how the switch from birch to spruce will influence albedo during the winter season with snow. Further research should seek to include the effects of changing albedo.

An uncertain component of the applied model, which was not tested with sensitivity analyses, is the release of carbon from the soil. At this point, the present paper simply adopted the assumptions on soil carbon dynamics made in Holtsmark (2015a,b). More information on this dynamics would be valuable and make the results in the present paper more reliable, especially if it had been combined with a model of how albedo is influenced.

Figures and tables

Figure 1. Development of the carbon pools of a single Birch stand in the scenario without harvesting or planting of new trees. Productivity index B14.

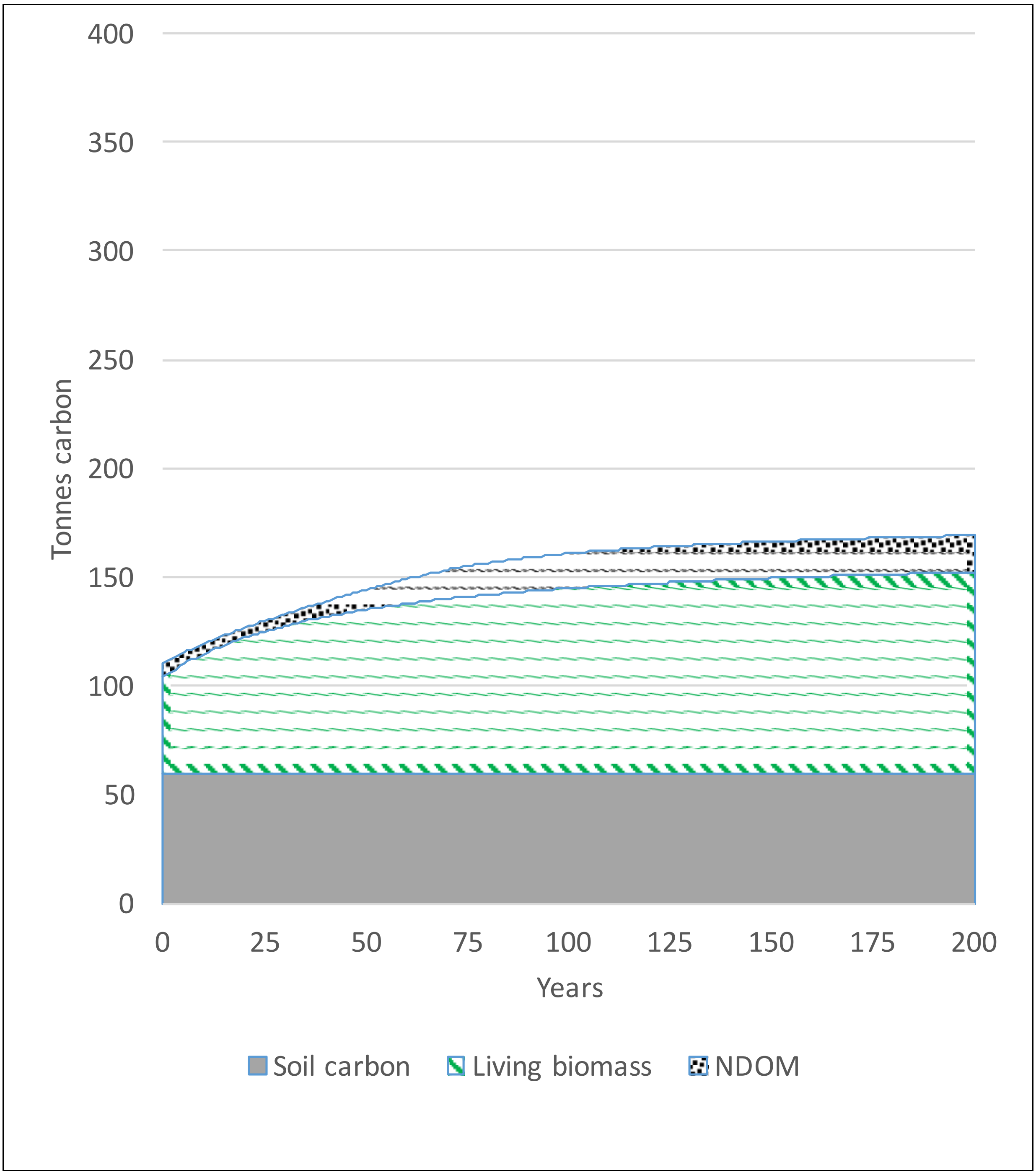


Figure 2. Development of the carbon pools of a single Spruce stand in a scenario with harvesting and tree planting. Productivity index of G14

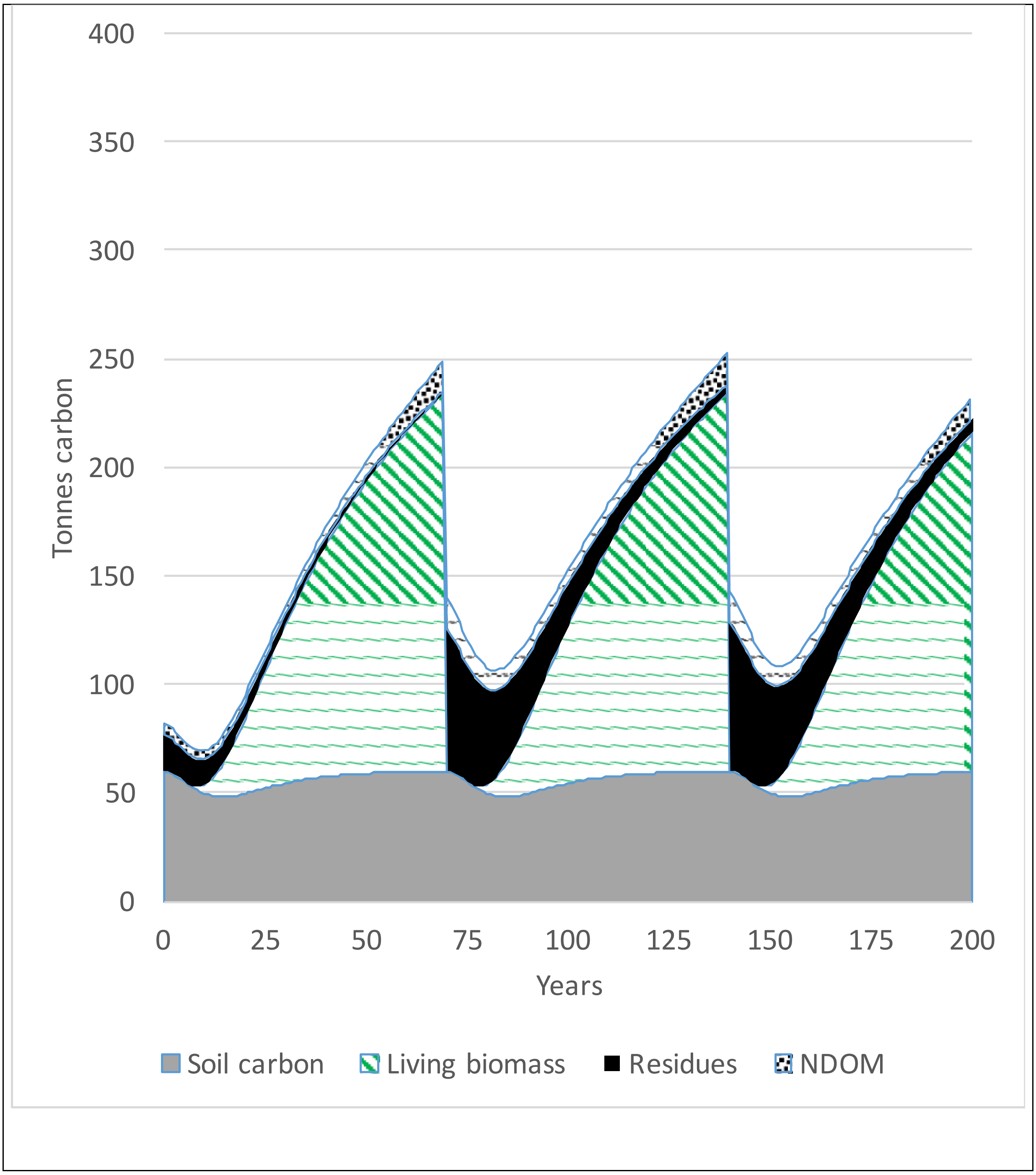
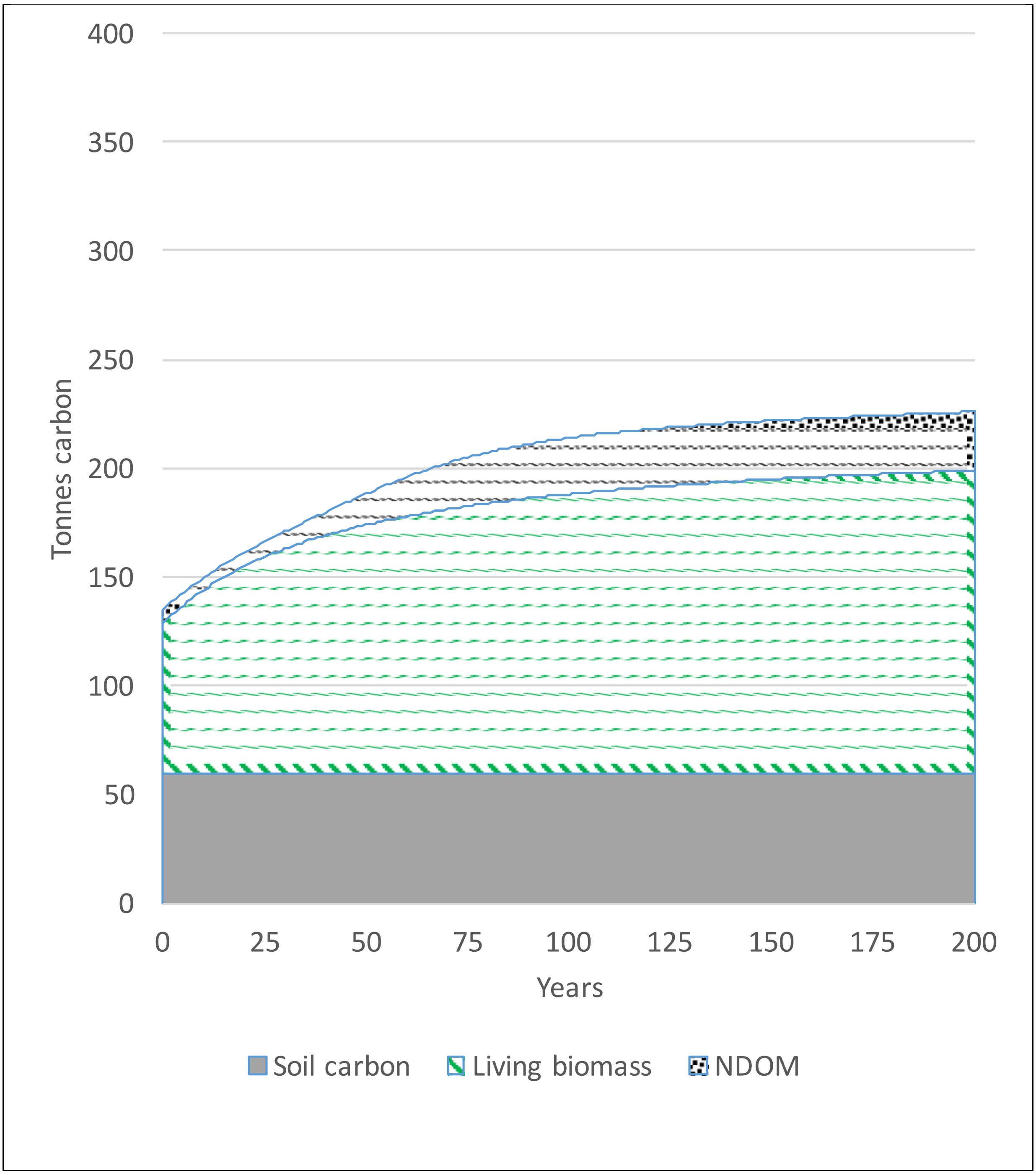


Figure 3. Development of the carbon pools of a single Birch stand in the scenario without harvesting or planting of new trees. Productivity index B20.



4. Development of the carbon pools of a single Spruce stand in a scenario with harvesting and tree planting. Productivity index of G20.

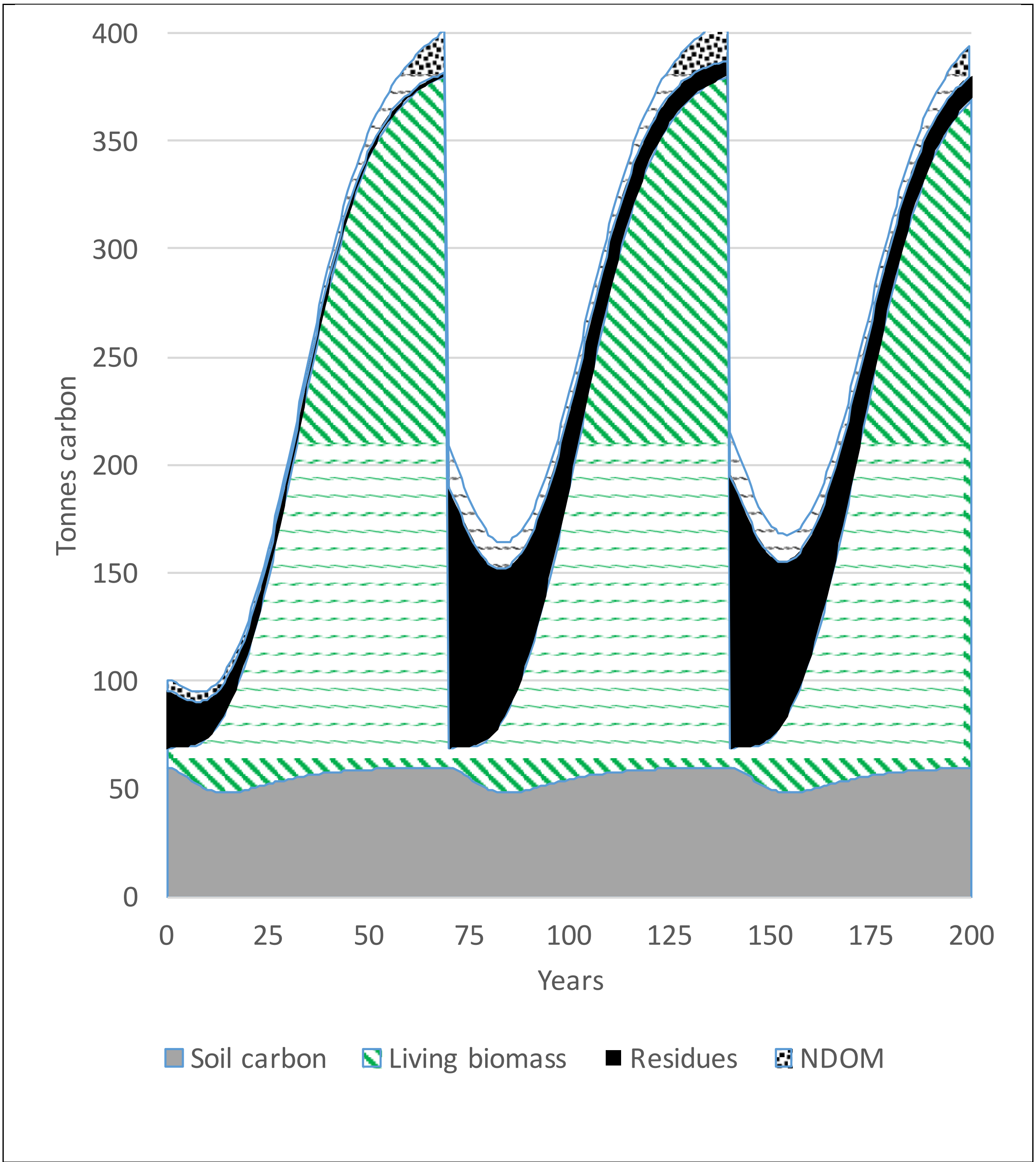


Figure 5. Share remaining in the atmosphere of a pulse of CO_2 at time 0.

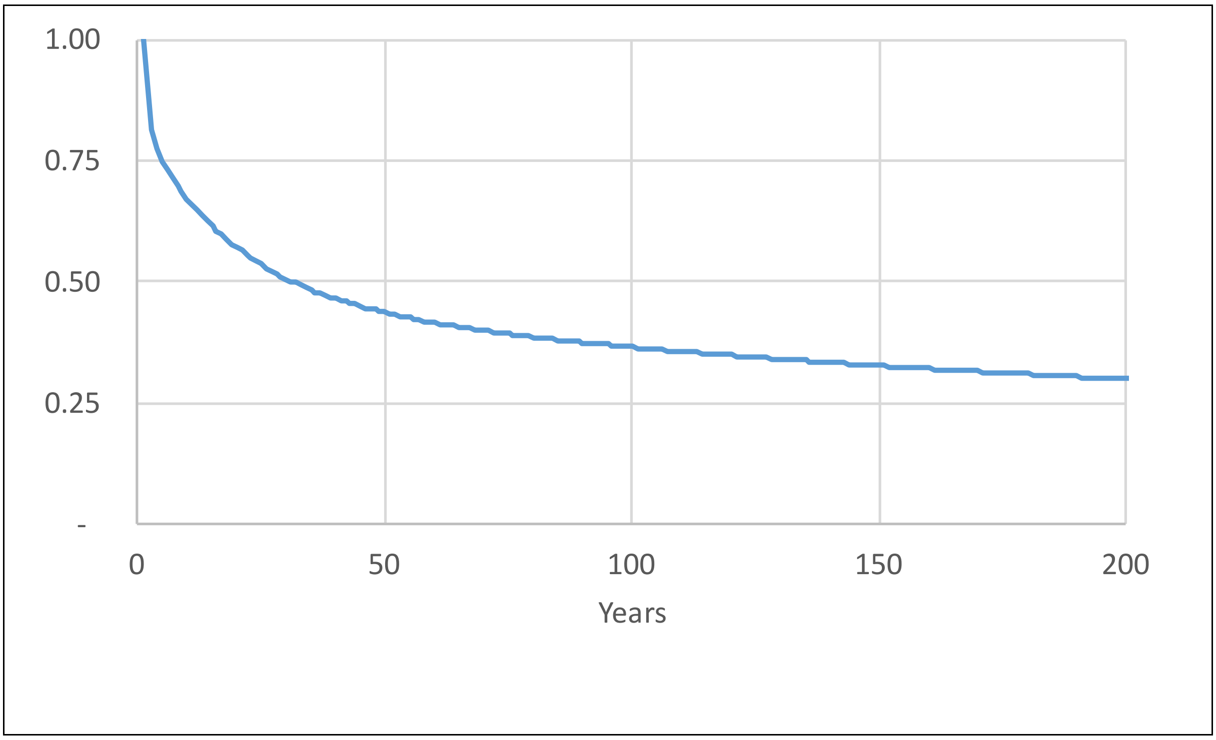


Table 1 Parameter values.

a_{B14}	*103.1*	y_0	0.217
a_{B20}	*154.5*	y_1	0.259
a_{G14}	*346.3*	y_2	0.338
a_{G20}	*326.2*	y_3	0.186
b_{B14}	*-25.4*	α_1	172.9
b_{B20}	*-24.3*	α_2	18.51
b_{G14}	*-48.2*	α_3	1.186
b_{G20}	*3.744*	β	0.01357
c_{G20}	*0.1099*	ω	0.04
θ	*0.48*	v_1	103.067
σ	*0.25*	v_2	0.0245
ϕ_{B14}	*0.140*	v_3	2.6925
ϕ_{B20}	*0.225*	δ_H	0
ϕ_{G14}	*0.32*	δ_{NH}	1
ϕ_{G20}	*0.45*	θ	0.48
k	*120*	m_1	-113.5
ρ	*0.06*	m_2	-0.09
		m_3	3.003

Figure 6. Development of the considered stand's carbon stock in both the reference scenario and the harvesting and tree planting scenario together with avoided accumulated fossil carbon emissions and the accumulated effect on the net flux of carbon to the atmosphere. Productivity index of B14 and G14

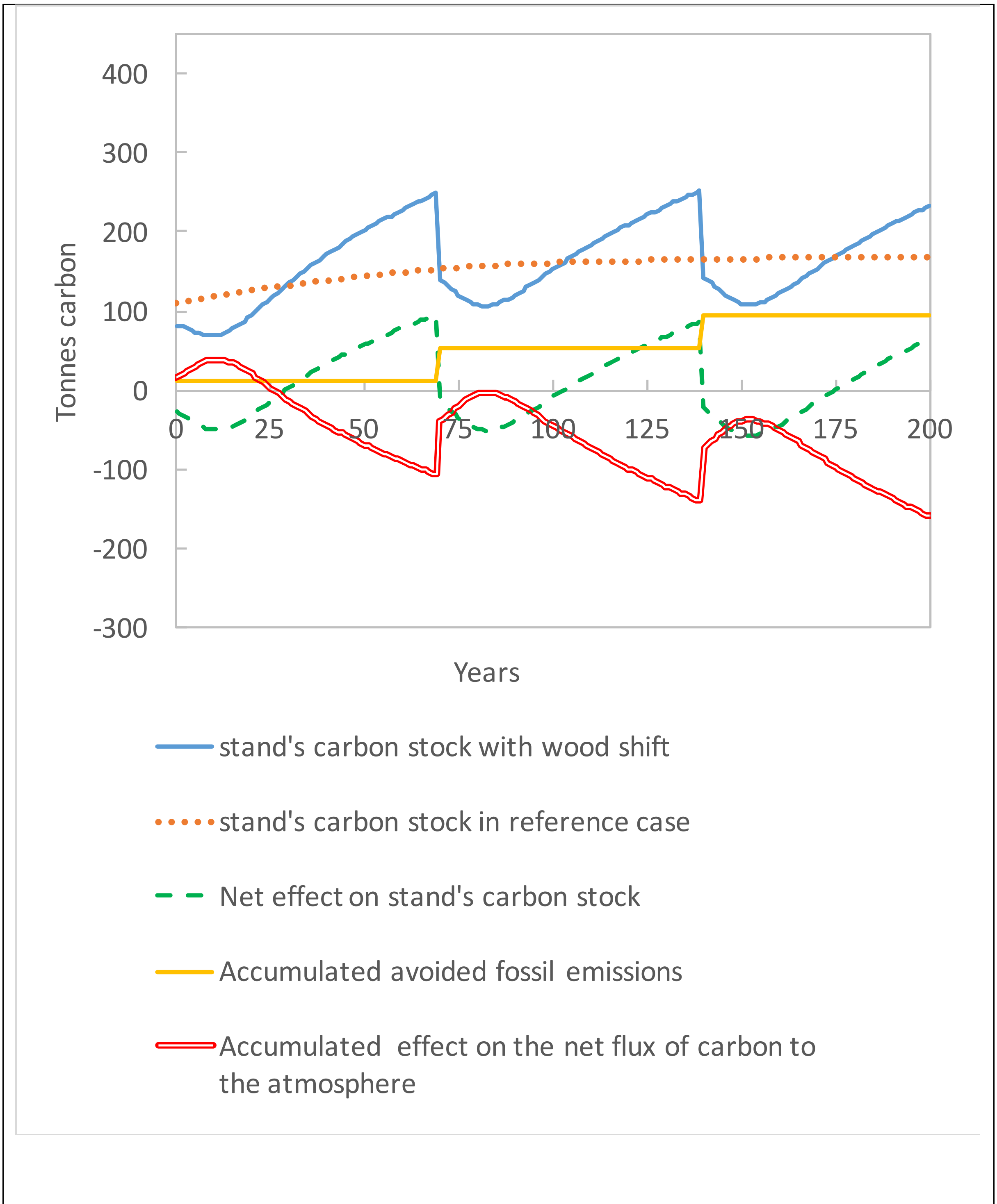


Figure 7. Development of the considered stand's carbon stock in both the reference scenario and the harvesting and tree planting scenario together with avoided accumulated fossil carbon emissions and the accumulated effect on the net flux of carbon to the atmosphere. Productivity index of B20 and G20

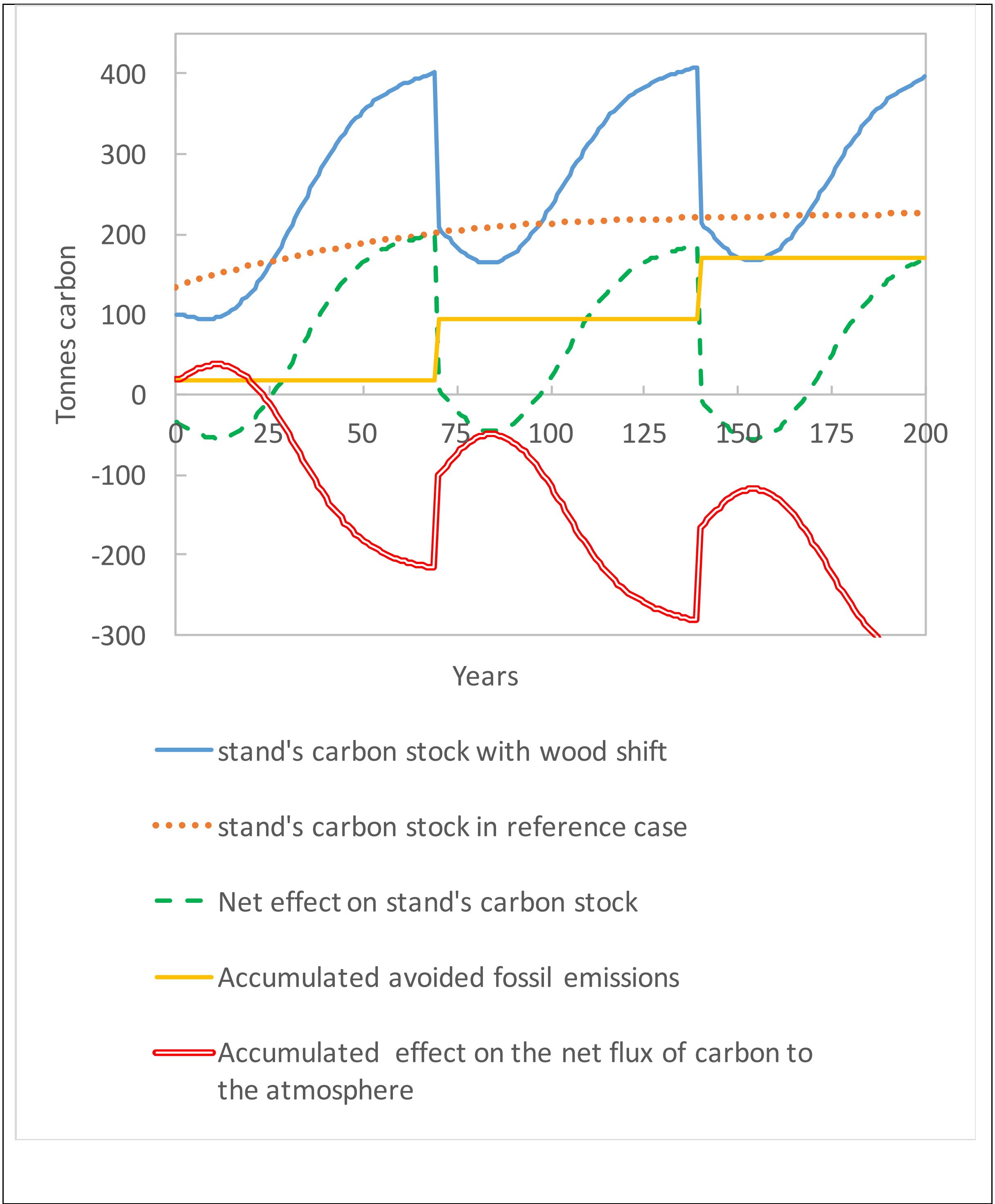


Figure 8. The blue, solid curve shows the net effect on atmospheric carbon of single stand harvesting and tree planting when the decay function of atmospheric carbon is taken into account. The red double curves shows the corresponding effect before the decay function is applied. The case with productivity indexes B14 and G14

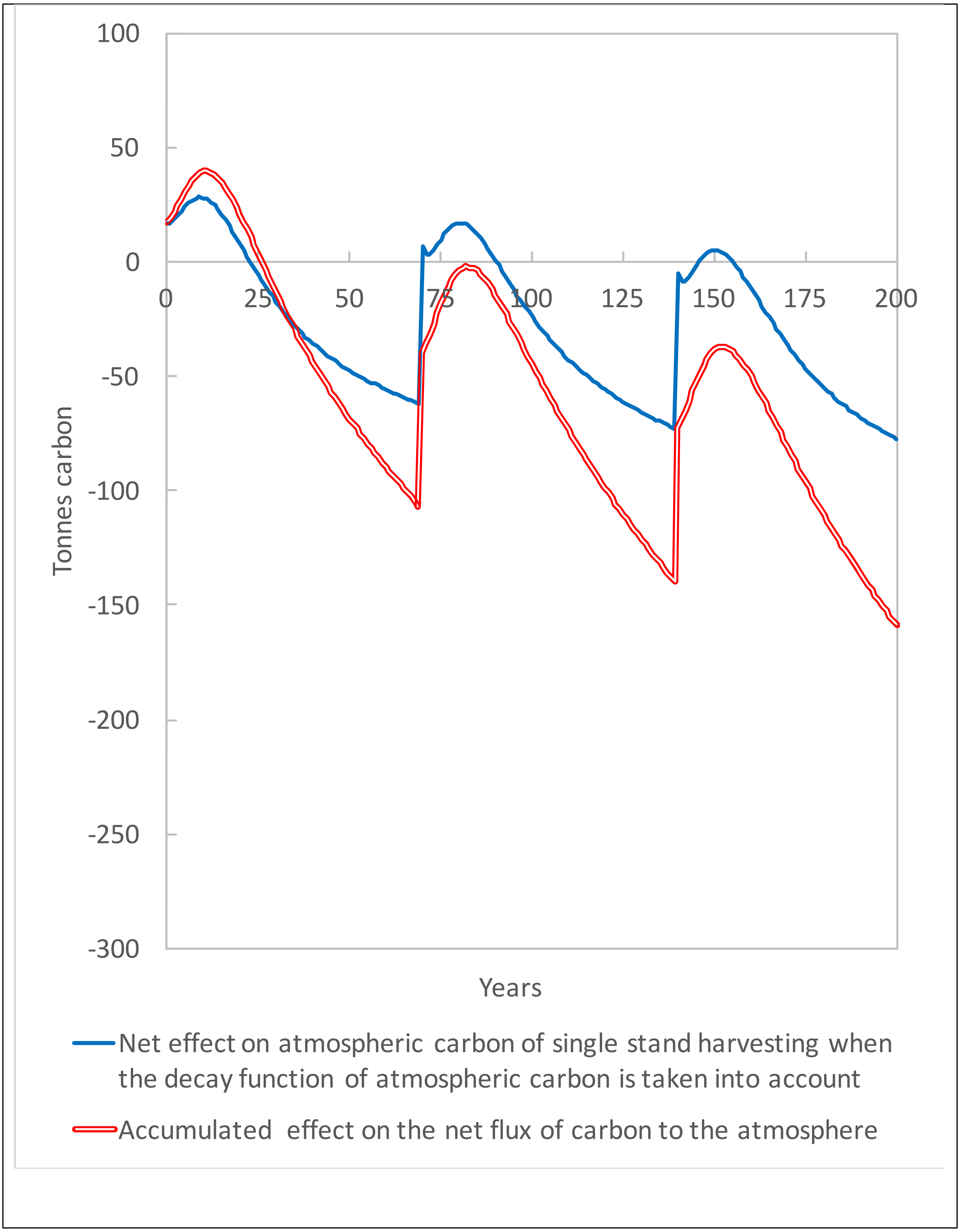


Figure 9. The blue, solid curve shows the net effect on atmospheric carbon of single stand harvesting and tree planting when the decay function of atmospheric carbon is taken into account. The red double curves shows the corresponding effect before the decay function is applied. The case with productivity indexes B20 and G20

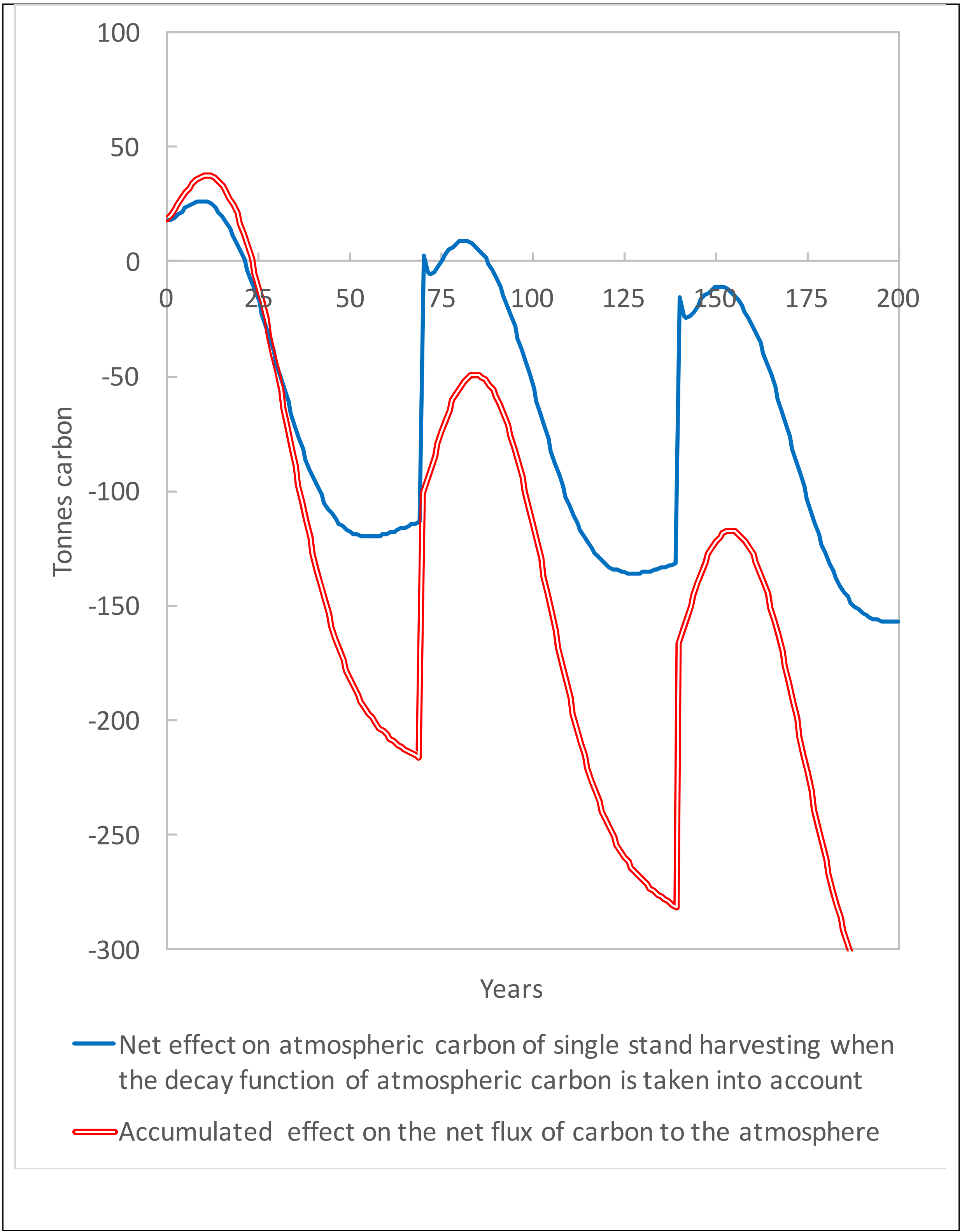


Figure 10. The red curve is the same as the blue, solid curve of Figure 8. Hence, it shows the net effect on atmospheric carbon of single stand harvesting and tree planting. The blue curve is the corresponding result of the harvesting and tree planting project taking place the subsequent year, and so forth. Hence, each of the thin curves represents each of the 20 different stands considered, respectively. These curves are measured along the left, vertical axis. The thick, black curve represents the total accumulated effect on atmospheric carbon of the 20 years program for consecutive harvesting and tree planting on the 20 stands. This accumulated, total effect is measured along the right, vertical axis. The case with productivity indexes B14 and G14

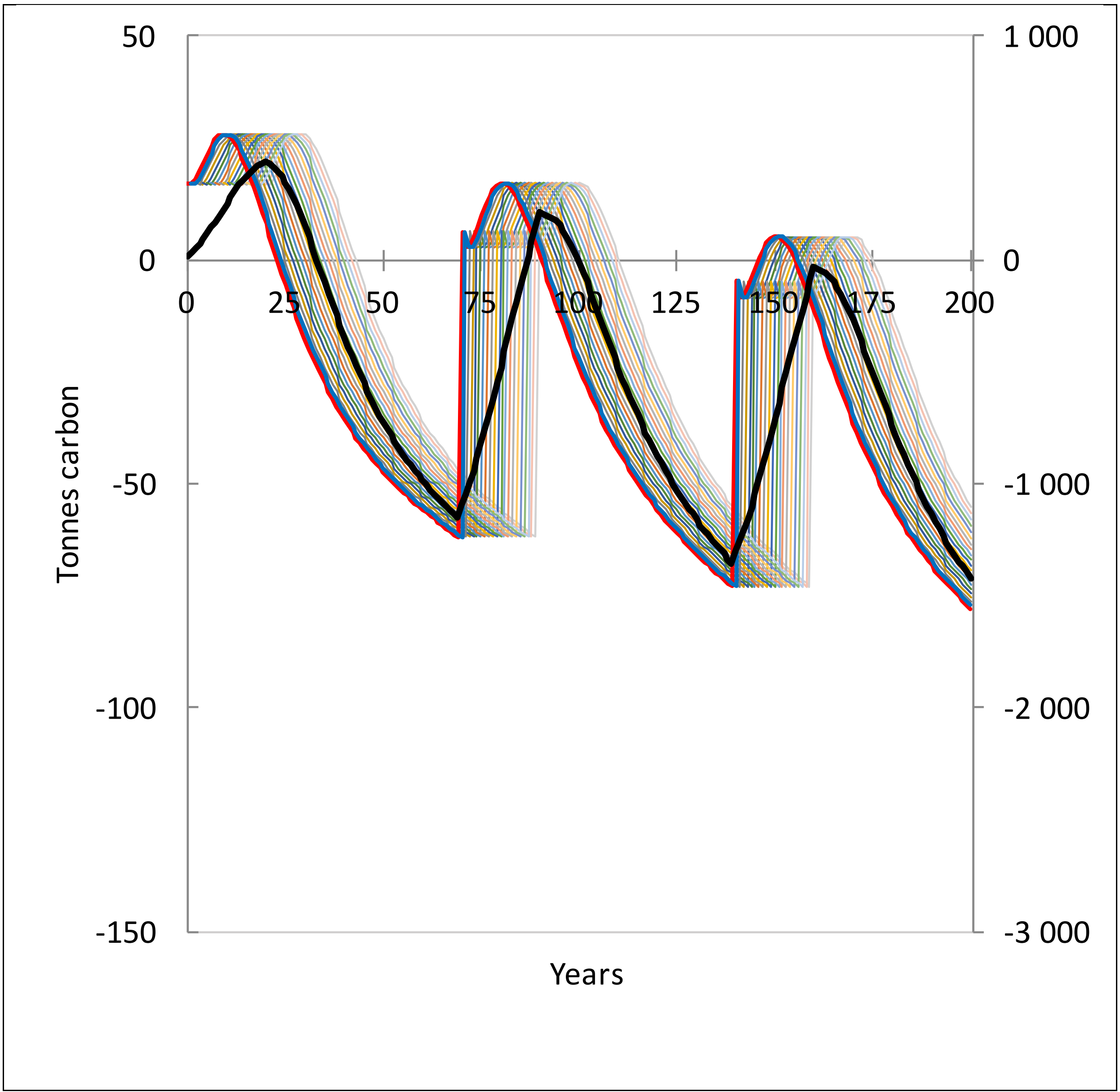


Figure 11. The red curve is the same as the blue, solid curve of Figure 9. Hence, it shows the net effect on atmospheric carbon of single stand harvesting and tree planting. The blue curve is the corresponding result of the harvesting and tree planting project taking place the subsequent year, and so forth. Hence, each of the thin curves represents the each of the 20 different stands considered, respectively. This curves are measured along the left, vertical axis. The thick, black curve represents the total accumulated effect on atmospheric carbon of the 20 years program for harvesting and tree planting on new areas and is measured along the right, vertical axis. The case with productivity indexes B20 and G20

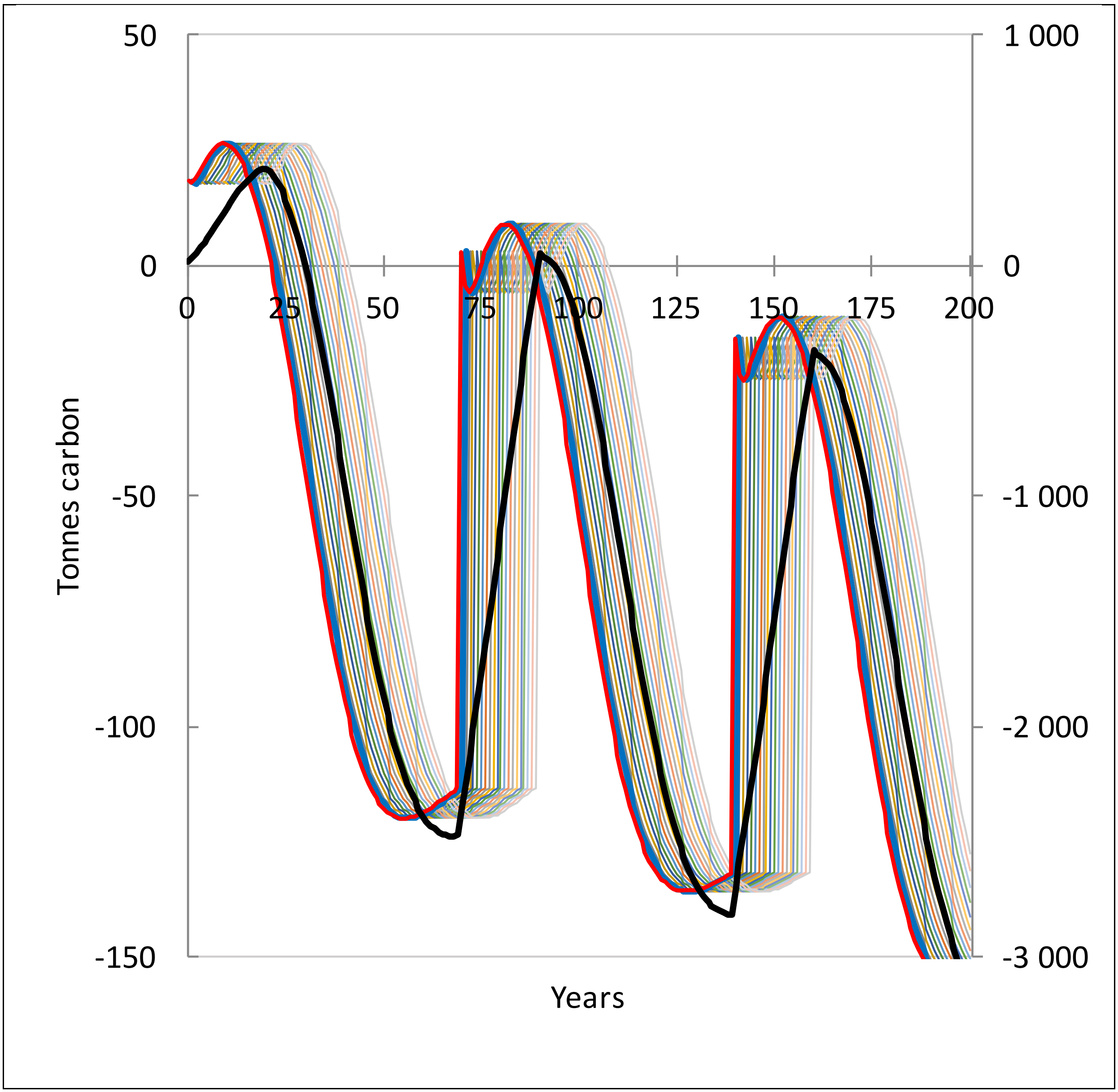


Figure 12. A scenario where bioenergy from the harvested biomass replaces 80 percent more fossil CO_2 emissions as assumed in the main cases. The curves are explained in the captions to Figures 10 and 11. The case with productivity indexes B14 and G14

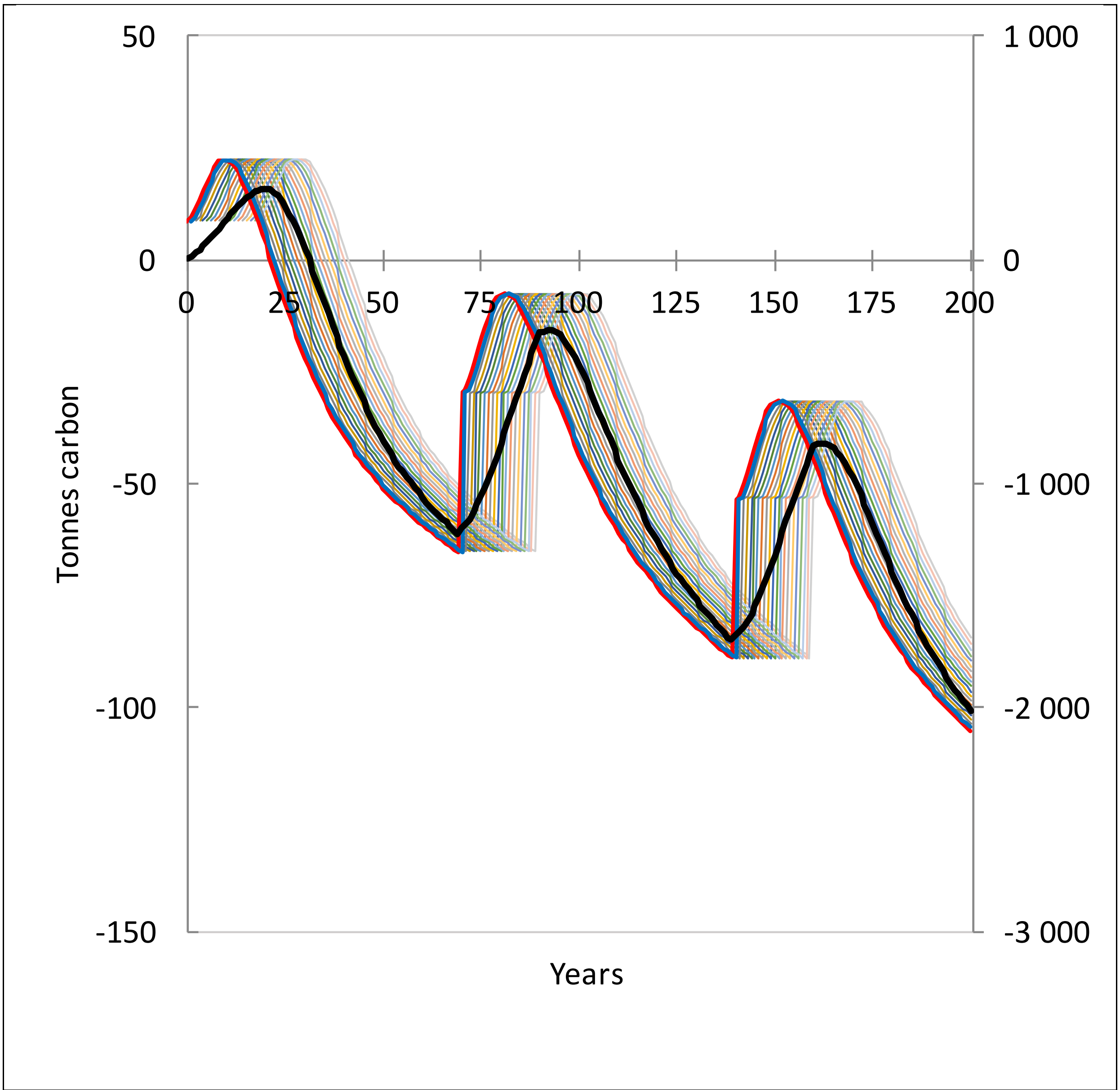


Figure 13. A scenario where bioenergy from the harvested biomass replaces 80 percent more fossil CO_2 emissions as assumed in the main cases. The curves are explained in the captions to Figures 10 and 11. The case with productivity indexes B20 and G20

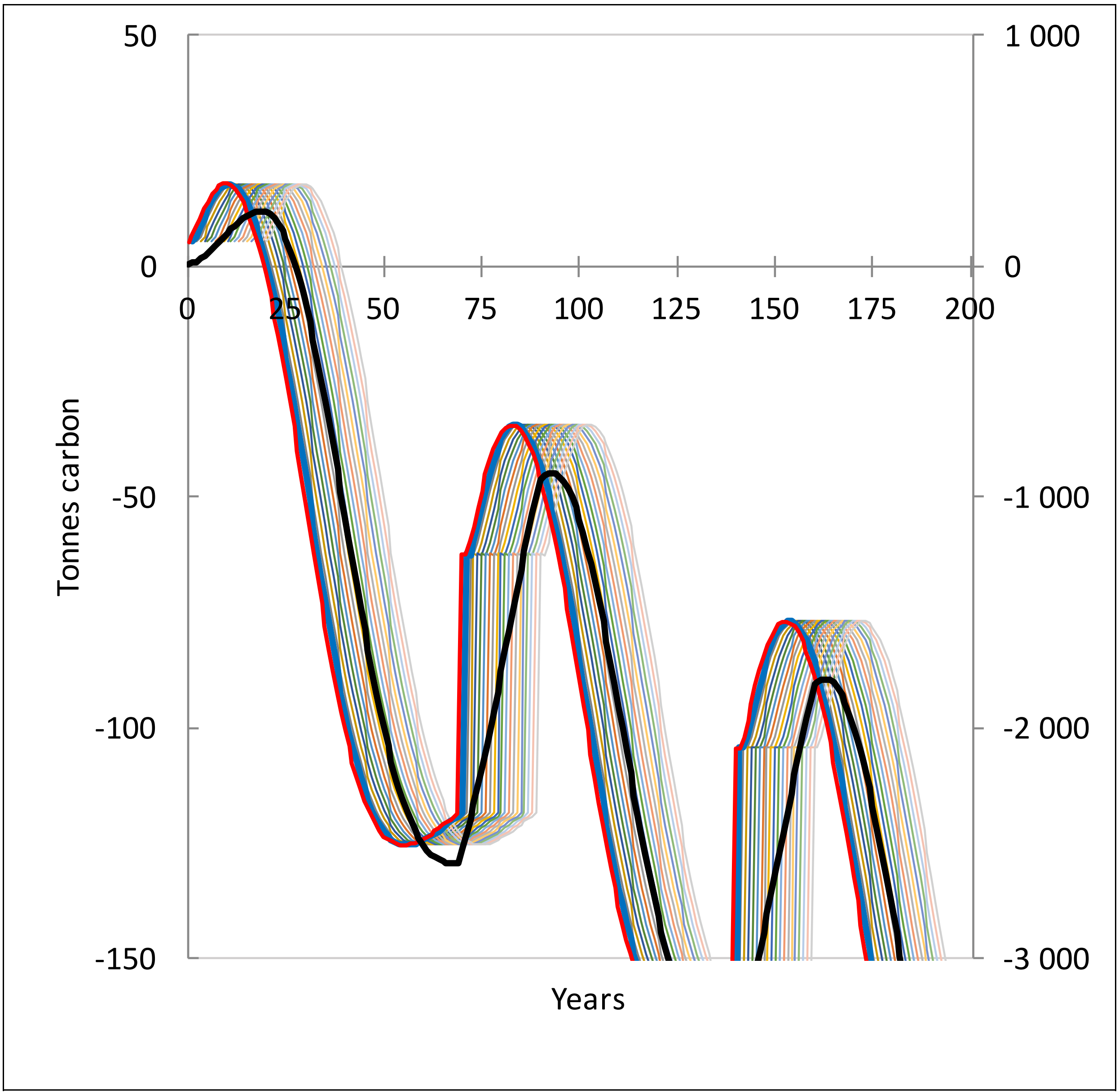


Figure 14. A scenario where bioenergy from the harvested biomass replaces 80 percent more fossil CO_2 emissions as assumed in the main cases and where harvesting of the new trees does not take place. The curves are explained in the captions to Figures 10 and 11. The case with productivity indexes B14 and G14

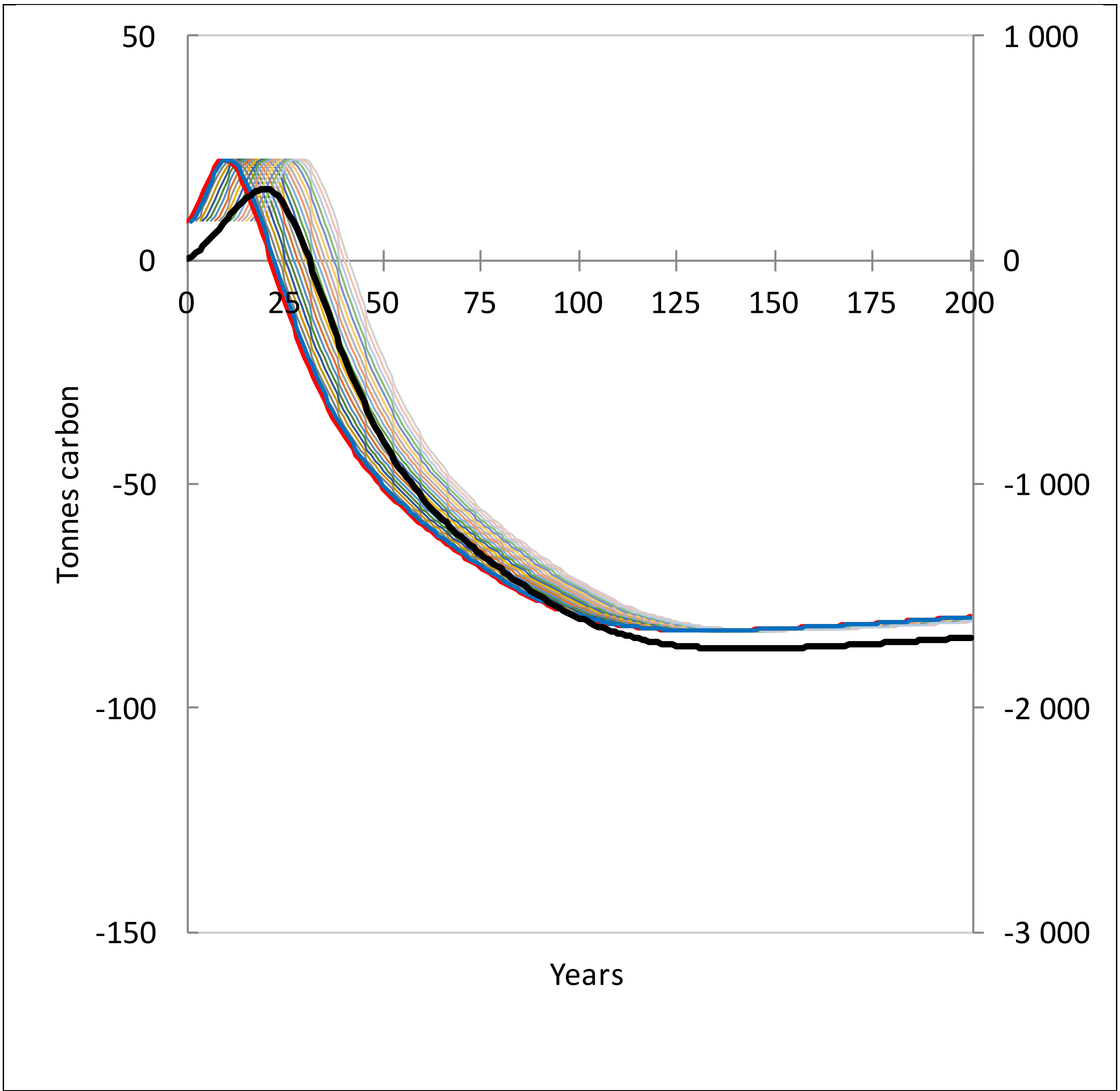


Figure 15. A scenario where bioenergy from the harvested biomass replaces 80 percent more fossil CO_2 emissions as assumed in the main cases and where harvesting of the new trees does not take place. The curves are explained in the captions to Figures 10 and 11. The case with productivity indexes B20 and G20

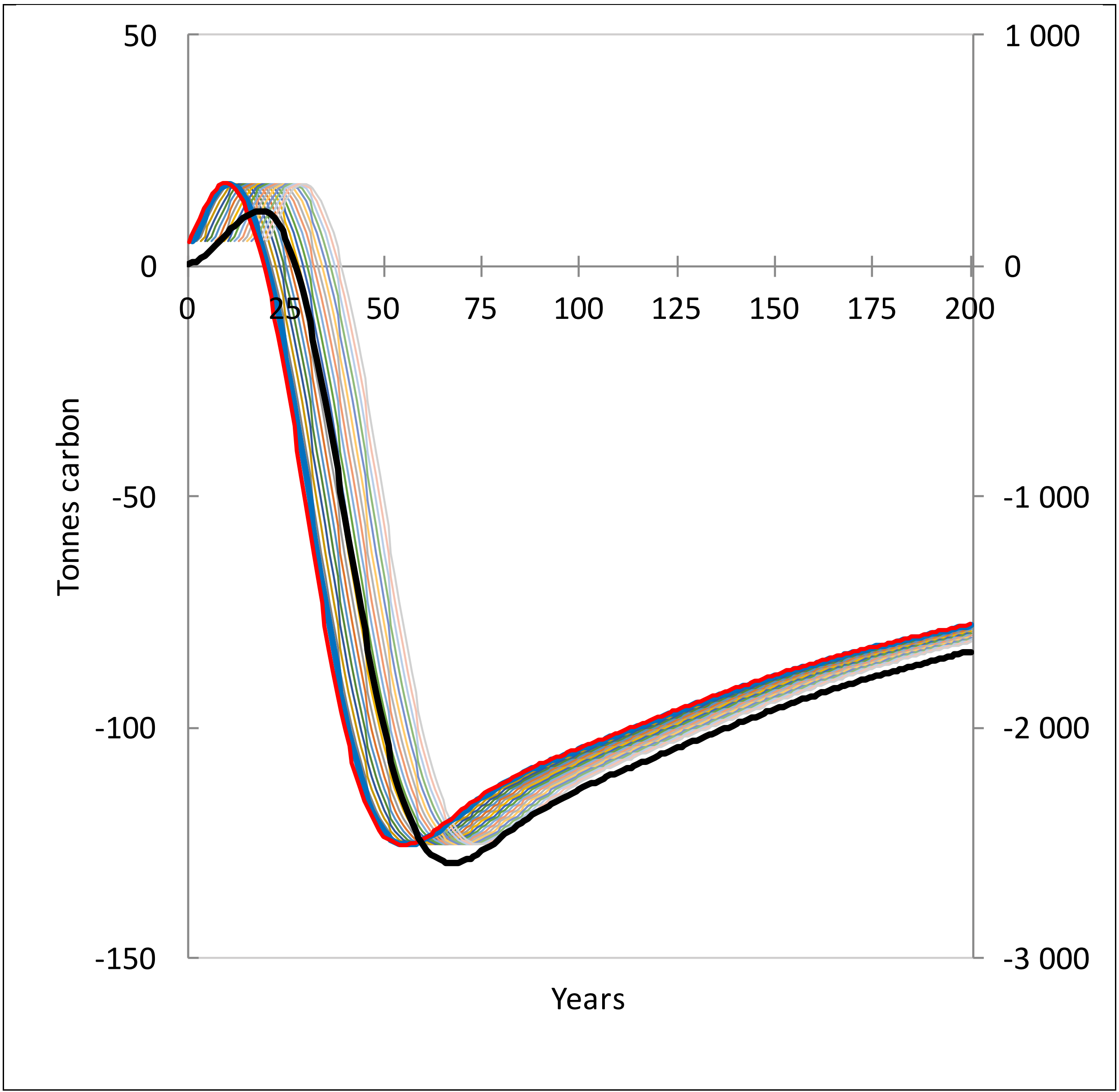


Figure 16. A case where the stand at *t* =0 has 10 year old birch trees and where bioenergy from the harvested biomass replaces 80 percent more fossil CO_2 emissions as assumed in the main. Productivity index of B14 and G14

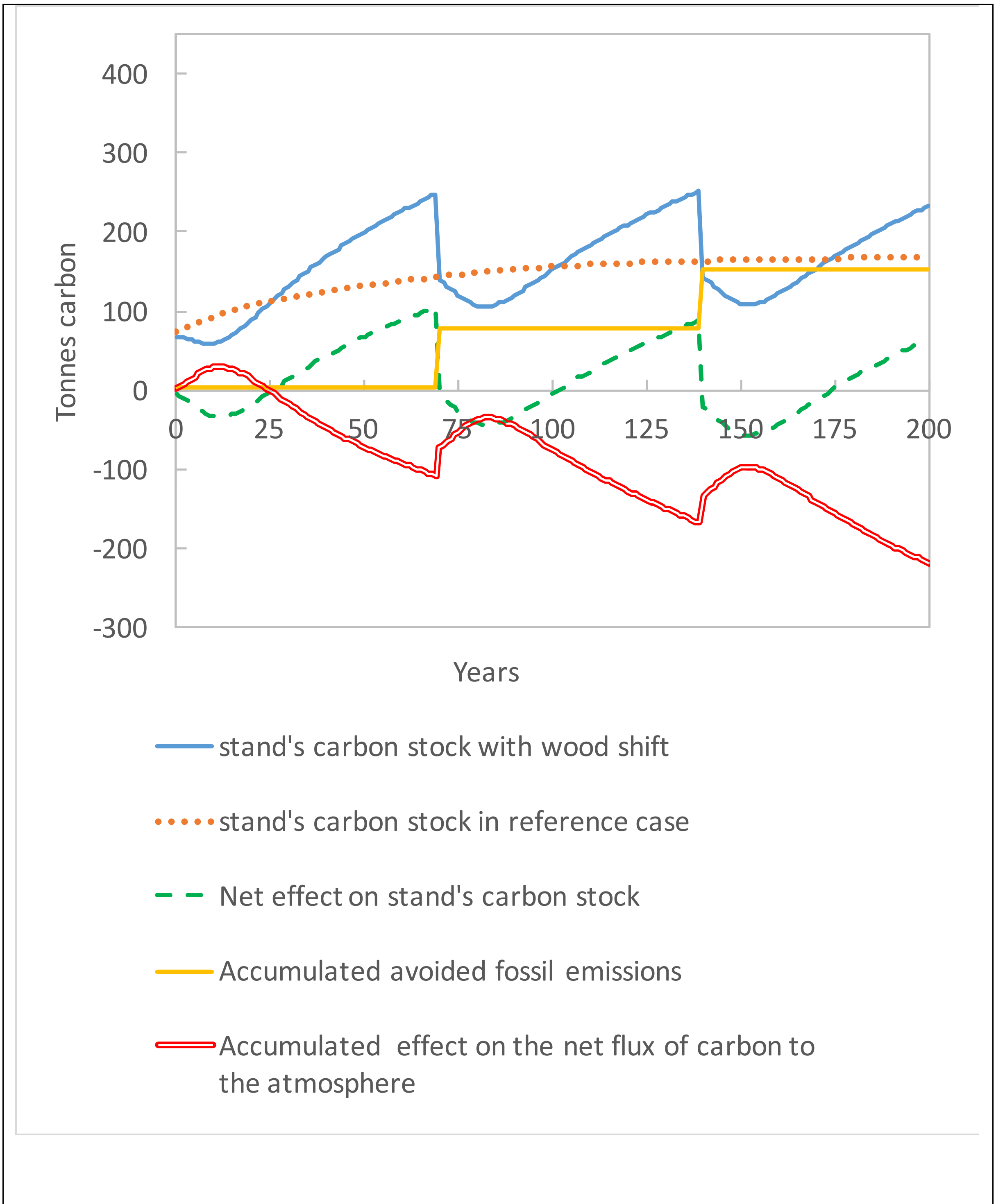


Figure 17. A case where the stand at *t* =0 has 10 year old birch trees and where bioenergy from the harvested biomass replaces 80 percent more fossil CO_2 emissions as assumed in the main. Productivity index of B20 and G20

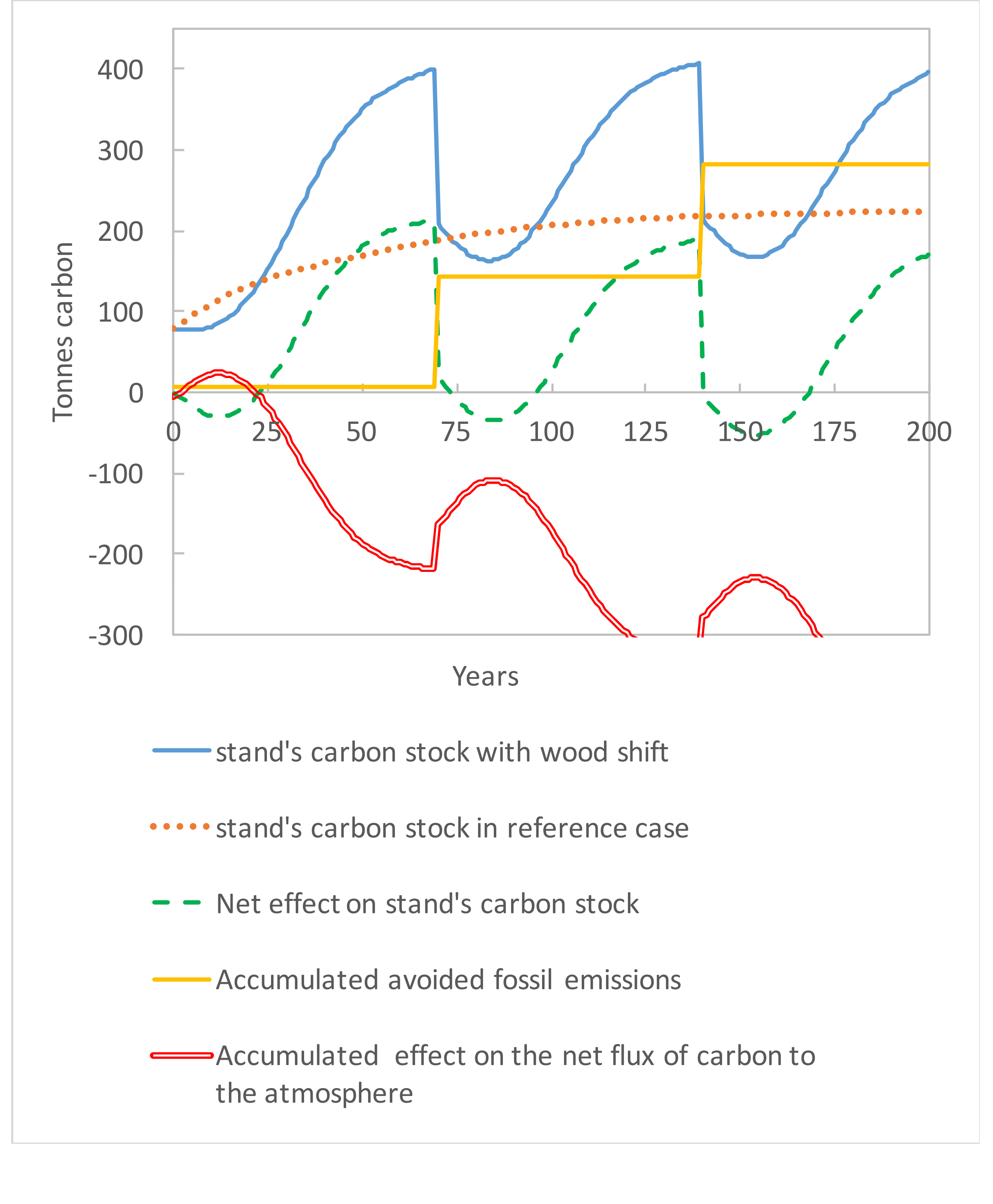


Figure 18. A case where the stand at *t* =0 has 10 year old birch trees and where bioenergy from the harvested biomass replaces 80 percent more fossil CO_2 emissions as assumed in the main. Productivity index of B14 and G14

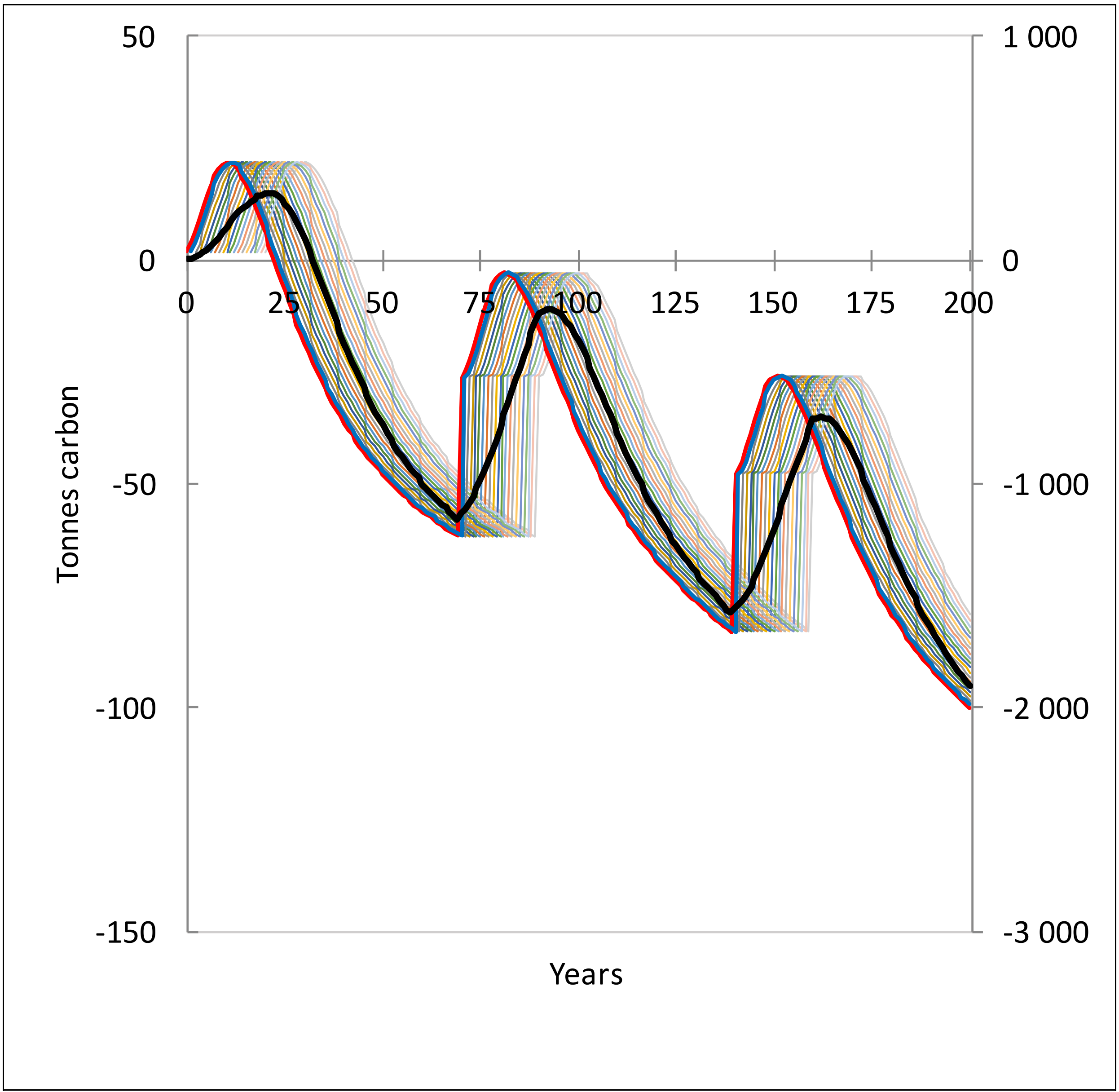
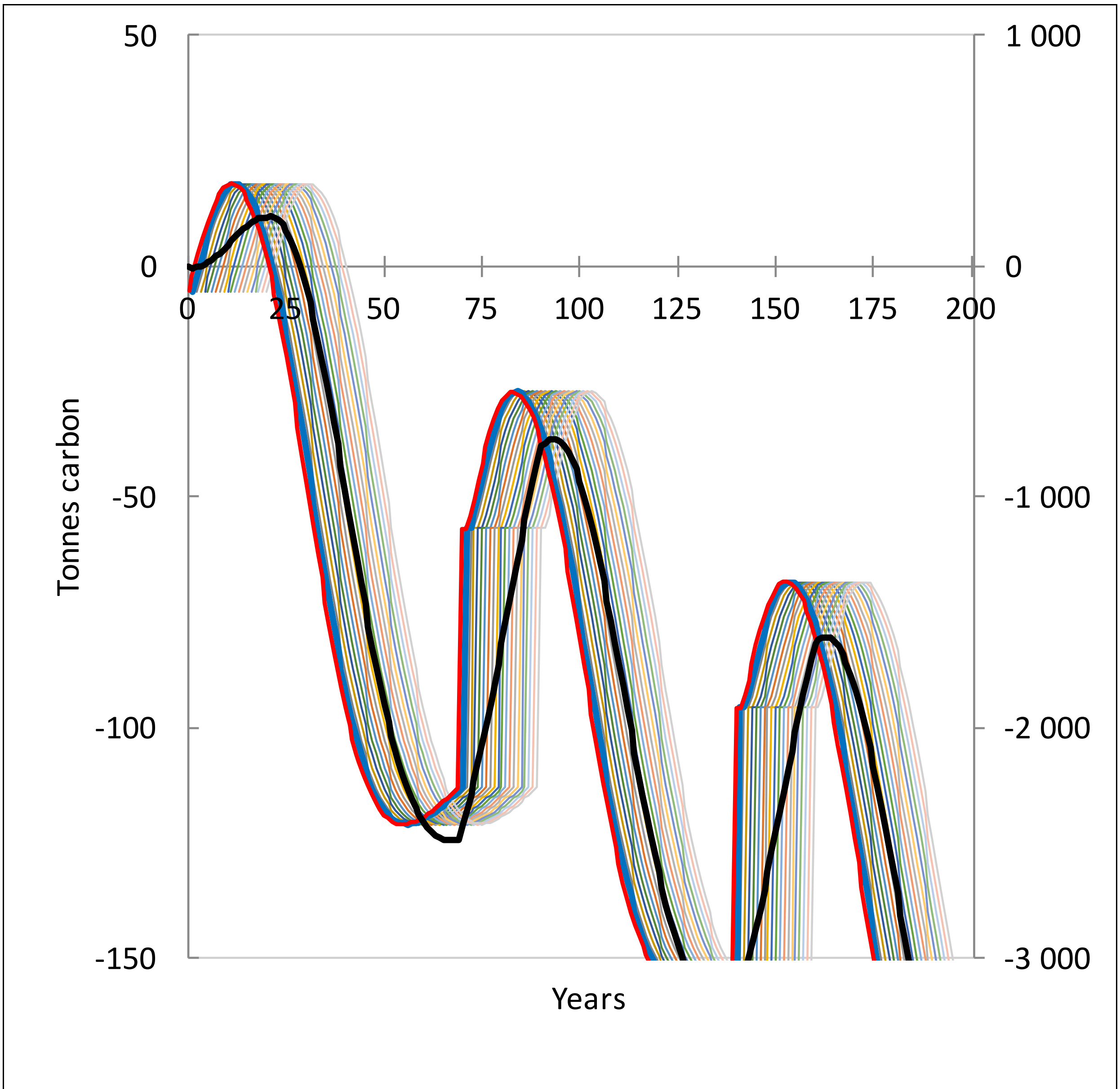


Figure 19. A case where the stand at *t* =0 has 10 year old birch trees and where bioenergy from the harvested biomass replaces 80 percent more fossil CO_2 emissions as assumed in the main. Productivity index of B20 and G20



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