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Abstract:
Traditionally, wood fuels, like other bioenergy sources, have been considered carbon neutral because the amount of CO_2 released can be offset by CO_2 sequestration due to the regrowth of the biomass. Thus, until recently, most studies assigned a global warming potential (GWP) of zero to CO_2 generated by the combustion of biomass (biogenic CO_2). Moreover, emissions of biogenic CO_2 are usually not included in carbon tax and emissions trading schemes. However, there is now increasing awareness of the inadequacy of this way of treating bioenergy, especially bioenergy from boreal forests. Holtsmark (2014) recently quantified the GWP of biogenic CO_2 from slow-growing forests (GWPbio), finding it to be significantly higher than the GWP of fossil CO_2 when a 100-year time horizon was applied. Hence, the climate impact seems to be even higher for the combustion of slow-growing biomass than for the combustion of fossil carbon in a 100-year timeframe. The present study extends the analysis of Holtsmark (2014) in three ways. First, it includes the cooling effects of increased surface reflectivity after harvest (albedo). Second, it includes a comparison with the potential warming impact of fossil fuels, taking the CO_2 emissions per unit of energy produced into account. Third, the study links the literature estimating GWPbio and the literature dealing with the carbon debt, and model simulations estimating the payback time of the carbon debt are presented. The conclusion is that, also after these extensions of the analysis, bioenergy from slow-growing forests usually has a larger climate impact in a 100-year timeframe than fossil oil and gas. Whether bioenergy performs better or worse than coal depends on a number of conditions.

Keywords: Bioenergy, boreal forests, climate change, carbon, albedo, fossil fuels

JEL classification: Q23, Q32, Q42

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Sammendrag

Tradisjonelt har trevirke, som andre bioenergikilder, vært ansett som karbonnøytralt fordi mengden CO_2 som frigjøres kan bli motvirket av CO_2-fangst ved gjenvekst av biomassen. Inntil nylig har derfor de fleste studier av bioenergi tilordnet en GWP-indeks på null til CO_2 som utvikles ved forbrenning av biomasse (biogen CO_2). Utslippene av biogen CO_2 er vanligvis heller ikke inkludert i ordninger for karbonskatt og kvotehandel. Det er imidlertid nå økende bevissthet om utilstrekkeligheten i denne måten å behandle bioenergi på, spesielt bioenergi fra boreal skog. Holtsmark (2014) kvantifiserte GWP av biogen CO_2 fra saktevoksende skog (GWPbio), og fant at oppvarmingspotensialet for biogen CO_2 er betydelig høyere enn GWP av fossilt CO_2 når en 100-års tidshorisont ble brukt. Derfor synes klimapåvirkningen å være enda høyere for forbrenning av saktevoksende biomasse enn for forbrenning av fossilt karbon, dersom man har et 100-års tidsperspektiv. Denne studien utvider analysen i Holtsmark (2014) på tre måter. For det første inkluderes den avkjølende effekten av økt overflatereflektivitet etter hogst (albedo). For det andre foretas en sammenligning med oppvarmingseffekten av bruk av fossilt brensel når man tar i betraktning CO2-utslipp per energienhet. For det tredje lages en forbindelseslinje mellom litteraturen som anslår GWPbio og litteraturen som omhandler karbongjeld. Modellsimuleringer som gir anslag på tilbakebetalingstid på karbongjeld presenteres. Konklusjonen er at bioenergi fra saktevoksende skog vanligvis har en større klimapåvirkning i en 100 - års tidsramme enn fossil olje og gass. Om bioenergi kommer bedre eller dårligere ut enn kull, avhenger av en rekke forhold.

Introduction

Traditionally, bioenergy has been considered carbon neutral because the released carbon is absorbed by the harvested crops' regrowth. Thus, CO_2 released from the combustion of bioenergy has until recently been assigned a GWP of zero in most LCA analyses; see, for example, Bright and Strømman (2009) and Sjølie *et al.* (2010). For the same reason, no country imposes taxes on CO_2 emissions from the combustion of bioenergy, and firms included in the European Union emissions trading market are not committed to acquiring and surrendering allowances for CO_2 emissions from the combustion of bioenergy.

There is now broad agreement that biofuels from forests should not be considered carbon neutral; see, for example, Chum *et al.* (2012), Friedland and Gillingham (2010), Haberl (2013), Haberl *et al.* (2012a,b), Holtsmark (2012, 2013a), Hudiberg *et al.* (2011), Schulze *et al.* (2012), and Searchinger *et al.* (2009). One argument is that there is a time lag between the harvesting and full regrowth of the forest. In addition, harvesting influences the dynamics of the harvested stands' carbon pools. For example, after harvesting there will often be a net release of carbon from the soil layer. More importantly, however, if the forest is not harvested, there will usually be further growth and accumulation of both dead and living biomass on the stand. Thus, to estimate the potential climatic effects of harvesting, the harvest scenario must be compared to a no-harvest scenario that includes a description of the stand's carbon dynamics in that case (Faustmann 1849, Samuelson 1976, Scorgie and Kennedy 1996, Helin *et al.* 2013, Holtsmark 2013b, Olsson *et al.* 1996).

If bioenergy should no longer be considered carbon neutral, the question is how its climate impact can be quantified, for example in LCA analyses, or in other assessments of the climatic properties of bioenergy. One possibility is to use the well-known concept of *global warming potential* (GWP). This is a frequently used metric when it is necessary to compare the climate impacts of different greenhouse gases (GHGs) with each other. GWP quantifies the cumulative potential warming effect of a pulse of GHGs over a specified period, taking into account its absorption of infrared radiation and atmospheric lifetime. GWP is a relative measure and the GWP of CO_2 is assigned the ratio 1.

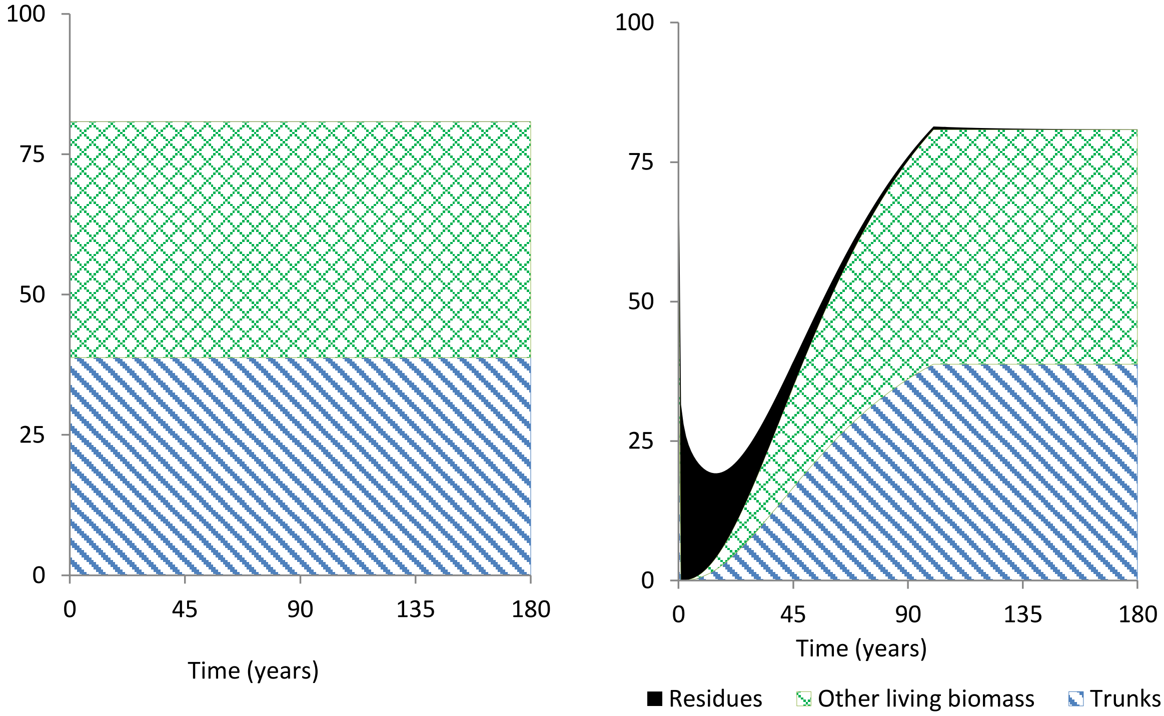
Clearly, CO_2 released by the combustion of biomass has exactly the same climatic impact as CO_2 released by the combustion of fossil fuels. However, taking into account that the harvesting of biomass influences the future time profile of the carbon uptake from the harvested stand, it could be argued that CO_2 released from the combustion of biomass has a different *net* climatic effect compared to CO_2

from fossil fuels. Therefore, when taking regrowth into account, Cherubini *et al.* (2011a) introduced the concept $GWP_{bio,}$ and estimated this metric to be 0.43 when they considered a stand in a slow-growing forest that was harvested at the age of 100 years. Later, Cherubini *et al.* (2011b, 2012), Bright *et al.* (2012), Guest *et al.* (2012), and Pingoud *et al.* (2011) presented estimates of GWP_{bio} in the interval 0.34 – 0.62 when slow-growing forest stands were considered. The fact that these estimates are significantly below 1.0 indicates that, from a climate perspective, bioenergy from slow-growing forests is better than fossil fuels.

However, Holtsmark (2014) showed that the abovementioned contributions had some methodological weaknesses. Bright *et al.* (2012), Cherubini *et al.* (2011a, 2011b, 2012), and Pingoud *et al.* (2011) applied models of a forest stand that did not include important effects of harvesting on the dynamics of carbon pools, such as residues, natural deadwood, and carbon. Moreover, only Pingoud *et al.* (2011) included a realistic baseline scenario. The other studies made the simplifying assumption that, if not harvested, there would be no further growth and accumulation of carbon in a mature stand. Guest *et al.* (2012) did include harvest residues in their analysis, but they did not include natural deadwood or effects on soil carbon, and they did not construct a realistic baseline scenario. A number of studies emphasize the importance of including these features (Asante & Armstrong 2012, Asante *et al.* 2011, Buchholz *et al.* 2013, Fontaine *et al.* 2007, Holtsmark *et al.* 2013, de Wit and Kvindesland 1999, Kjønaas *et al.* 2000, Johnson and Curtis 2001, Nakane and Lee 1995). Moreover, Bright *et al.* (2012), Cherubini *et al.* (2011b, 2012), and Guest *et al.* (2012) made the assumption that, in the harvest scenario, there is a sudden stop in the growth of biomass on the stand when the stand's age becomes equal to the stand's age at time of harvest in the previous rotation. As an illustration of these type simplifications, Figure 1, which is taken from Holtsmark (2014), shows the development of carbon stored in the stylized stand as modeled by Guest *et al.* (2012). Note how the stand's growth stops at a stand age of 90 years in the harvest scenario, while there is a fixed carbon stock in the no-harvest scenario. As shown in Holtsmark (2014), similar simplifications were made by Bright *et al.* (2012) and Cherubini *et al.* (2011a, 2011b, 2012). The simplifications are crucial to their conclusions.

Holtsmark (2014) presented an improved method for estimating the net warming impact of biofuels. First, the harvest scenario was compared to a no-harvest baseline scenario that took into account that accumulation of dead and living biomass will usually continue if the stand is not harvested. Second, the model that was introduced included the dynamics of the forest stand's main carbon pools, including harvest residues, the pool of natural deadwood, and all parts of growing trees, such as branches, tops, stumps, and roots, in addition to the stems. The effects of harvesting on the pool of soil carbon were also modeled. Figure 2 illustrates the model setup in Holtsmark (2014).

Figure 1. Illustration of the development of carbon stored in the considered forest stand as modelled by Cherubini et al. (2012) and Guest et al. (2012). (a) The no-harvest scenario (b) The harvest scenario. The diagram is identical to Fig. 6 in Holtsmark (2014)



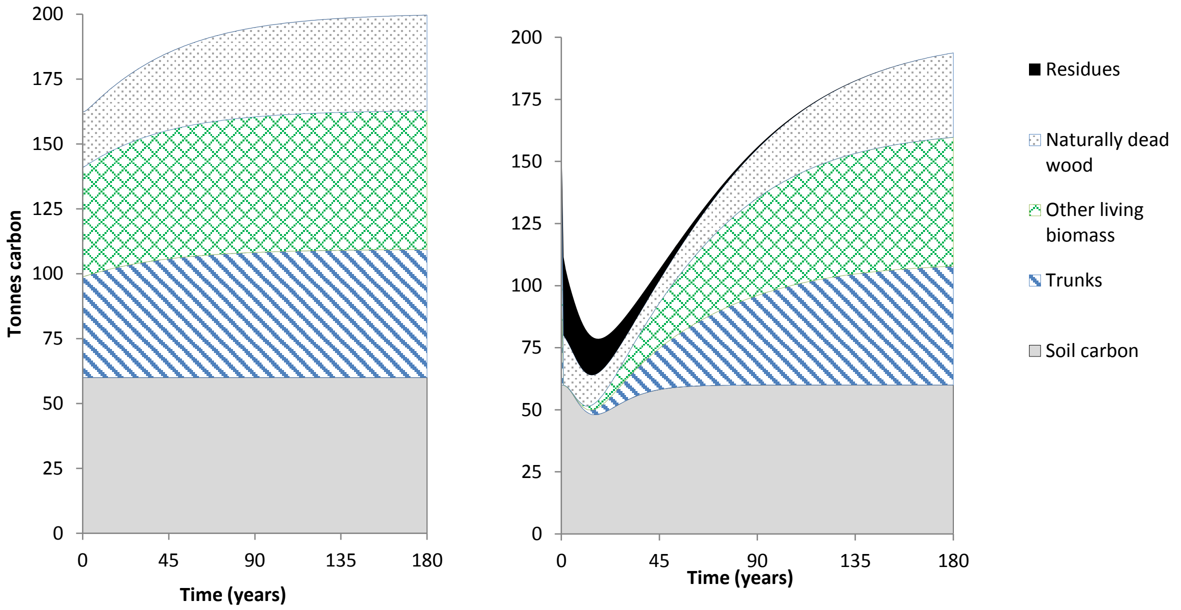
The simulation results presented in Holtsmark (2014) clearly demonstrated the importance of including all the forest stand's carbon pools in the model, as well as a realistic reference scenario. When a 100-year time horizon was applied to a forest stand aged 100 years, the resulting GWP_{bio} estimate was found to be 1.5, i.e., more than three times as high as the estimates of GWP_{bio} found by Cherubini *et al.* (2011a,b).

The contribution of the present paper is threefold. First, it improves the method of Holtsmark (2014) by taking into account a possible cooling effect of increased albedo after harvesting (Cherubini 2012, 2013). Second, the net warming impact of wood fuels is compared to the net warming impact of coal, oil, and gas when considering the fuels' respective warming impacts per unit of energy produced. Third, the single harvest approach taken in the abovementioned studies of GWP_{bio} is supplemented by simulations based on the landscape approach in order to show the time profile of how permanently increasing the use of bioenergy from slow-growing forest will cause global warming. This extension of the analysis builds a bridge between the literature on GWP_{bio} and the literature estimating the payback time of the carbon debt (Bernier 2013, McKechnie *et al.* 2011, Holtsmark 2012).

With regard to the conclusions that can be drawn from the analysis, it should be kept in mind that the present paper considers a typical Norwegian forest of medium productivity. To the extent that the considered stand is representative of large areas of boreal forests, the analysis has relevance beyond Norway's borders. However, until similar studies are conducted using data from boreal regions, the policy implications for other countries should not be exaggerated. Note also that the assumptions with regard to the albedo effect are entirely based on the estimates of albedo at a stand in Hedmark in the south-eastern part of Norway; see Cherubini *et al.* (2012, 2013). This is an area with a relatively long season with snow cover and thus significant albedo from open land. Other areas in Norway and other boreal forests are likely to have very different albedo patterns. Hence, too general conclusions should not be drawn based on the relatively high albedo effects found in this study.

It should be noted here that the present paper does not take into consideration the climatic effects of aerosols from forests, although the cooling effect of such aerosols could be significant; see, for example, Spracklen *et al.* (2008) or Ehn *et al.* (2014). This could mean that the present work is too optimistic as regards the climatic effects of wood fuels.

Figure 2. Illustration of the development of carbon stored in the considered forest stand as modelled in the present article. (a) The no-harvest scenario (b) The harvest scenario.



A discussion of the fruitfulness of the concept of GWPbio would be an important follow up to present paper. It is an important question whether this metric could be used, for example, when deciding the CO_2 tax on different energy sources. This is left to further research, however.

The outline of the paper is as follows. The next section briefly presents the model of the considered forest stand and the model for the accumulation of carbon in the atmosphere. Since the same model was applied in Holtsmark (2014), readers looking for details about how the dynamics of the forest stand were modeled, are directed to that paper. The section also introduces the model for albedo, before presenting the proposed method for calculating GWPbio. The third section presents the results. Finally, there is a section containing discussion and the conclusion.

Materials and methods

The model of a forest stand

The basis for the estimation of GWP_{bio} is a comparison of the no-harvest scenario and the harvest scenario, with respect to the time profile of the considered forest stand's total carbon stock and the corresponding net fluxes of CO_2 between the stand and the atmosphere. Hence, the model of the considered stand is quite important to the results. This model is only described briefly below since Holtsmark (2014) provides a detailed description of the model.

The point of departure is that the considered stand's age at time t=0 is 100 years. Two scenarios are considered. Either the stand is harvested (clearcutting) at time t=0, or the stand is not harvested. Figure 2 describes the development of the stand's carbon pools in the two cases.

The growth function for the trees on the stand was calibrated to fit into the standard production tables for Norway spruce of medium productivity provided in Braastad (1975). The volume of trunks is 194 m^3/ha at stand age 100 years. This is in agreement with the results of simulations using the Norwegian forest model AVVIRK-2000 (see Eid and Hobbelstad, 1999). These simulations indicate that a significant upscaling of harvesting in Norway would yield an average harvest of 194 m^3/ha. At the time of harvest (t = 0), the forest stand has a total carbon stock of 162 tC (before harvesting). In the harvest scenario, all stems of living trees are removed from the stand at time t = 0, with subsequent combustion giving rise to a pulse of CO_2 corresponding to the amount of carbon contained in the stems (39 tC). Hence, after harvesting at time t=0, the stand stores 123 tC (including soil carbon, residues left on the forest floor, and naturally dead wood); see Figure 2b. A case including the use of harvest residues was also considered, resulting in a correspondingly higher emission pulse at time t = 0 and correspondingly smaller subsequent emissions from the decomposition of residues (Repo *et al.* 2011, 2012). Note, however, that the numerical results could paint too optimistic a picture of the use of residues for energy purposes, as it was assumed that the removal of residues does not influence future growth or the release of soil carbon (Helmisaari *et al.* 2011, Palosuo *et al.* 2001).

New trees start growing after harvesting; see the hatched and cross-hatched areas in Figure 2b. Residues left on the forest floor decompose; see the black area. Moreover, natural deadwood (NDOM) that was present in the stand at the time of harvesting also gradually decomposes, while new, naturally dead biomass is generated; see the dotted area in Figure 2b.

As regards the dynamics of the soil carbon pool, it was assumed that harvesting results in some years with a net release of carbon from the soil. Thereafter, the soil carbon pool gradually returns to its original state; see Figure 2b. The development of the stand's carbon stock in the no-harvest baseline scenario is shown in Figure 2a. The point of departure is that the stand's age is 100 years at $t = 0$. Hence, at time $t = 0$ in the no-harvest scenario, the sizes of the carbon pools are the same as at time $t = 100$ in the harvest scenario, cf. Figures 2a and b. Moreover, in the no-harvest scenario, there is continued forest growth after $t = 0$, with a corresponding continued accumulation of natural deadwood. In the no-harvest scenario, the soil's carbon pool is assumed to be constant over time.

There is significant uncertainty about the likely development of the carbon stock of an old stand. However, in line with, e.g., Luyssaert *et al.* (2008) and Carey *et al.* (2001), I assumed continued accumulation of carbon even in old stands. As this is an uncertain part of the scenario, Holtsmark (2014) provided a sensitivity analysis with a significantly smaller accumulation of carbon in older stands.

Accumulation of carbon in the atmosphere and radiative forcing effects

The model for the lifetime of carbon in the atmosphere is the same model as applied in Holtsmark (2014) and Cherubini *et al.* (2011a, b, 2012); see those papers for details. The carbon lifetime model is based on Joos & Bruno (1996), Joos *et al.* (1996), and Joos *et al.* (2001). It is labeled the Bern 2.5CC carbon cycle model. It takes into account how a pulse of CO_2 leads to increased absorption of CO_2 by the terrestrial biosphere as well as the sea. The profile of the broken double-lined curve in Figure 3 depicts the remaining proportion at time t of a CO_2 pulse generated at time $t = 0$ from the combustion of an amount of fossil fuels (oil) in the no-harvest scenario. The Bern 2.5CC model is also applied to the pulse emission caused by combustion of the harvest and to the fluxes of CO_2 generated by the stand's growth and by the decomposition of natural deadwood and harvest residues left on the forest floor; see Holtsmark (2014) for further details.

To make the potential warming effect of CO_2 emissions comparable to the cooling effect of increased albedo, it is necessary to model the additional radiative forcing of additional carbon in the atmosphere, here labelled $\Delta RF(t)$. Following Forster *et al.* (2007), the additional RF from an additional amount $\Delta A(t)$ of carbon is assumed to be

$$\Delta RF(t) = z \cdot \ln(1+\Delta A(t)/A_0(t)) \text{ W/m}^2,$$

where $A_0(t)$ is the amount of carbon in the atmosphere in the absence of the considered pulse and z is a parameter.

In most simulations, it is assumed that $z = 5.35$, which means that the climate sensitivity of CO_2 is 3 °C. However, a case will also be considered where a sensitivity of 4.5 °C is assumed, which means that $z = 7.55$.

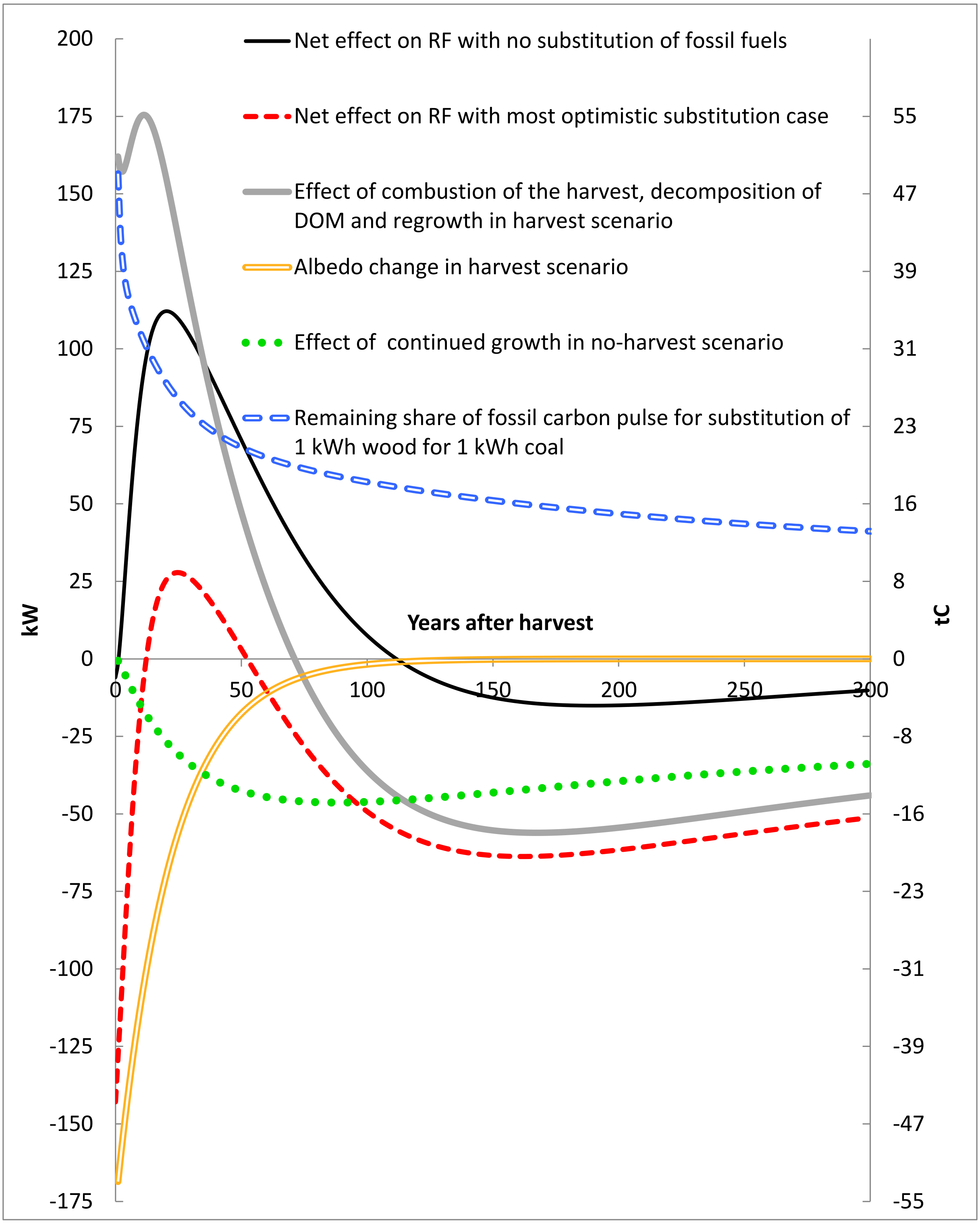
First, note that it follows from (1) that the amount of additional RF from a carbon pulse is influenced by the concentration of CO_2 in the atmosphere. As the atmospheric concentration is increasing, additional RF from additional CO_2 is decreasing. However, Caldeira and Kasting (1993) found that, since the lifetime of CO_2 in the atmosphere is likely to be increasing as the atmospheric concentration is increasing, it is a sound approximation to fix the background CO_2 concentration at the current level in this type of analysis. This was therefore done; see equation (2). Given that the surface of the planet is approximately $5.10072 \cdot 10^{14}$ m², the modeled additional RF of an additional amount of carbon is

$$(2) \qquad \Delta RF(t)=5.10072 \cdot 10^{14} \cdot z \cdot \ln(1+\Delta A(t)/A_{2014}) \text{ W},$$

where A2014 is the current amount of carbon in the atmosphere, set to 855 GtC.

Figure 3 illustrates how the combination of the model works. As already mentioned, the broken double-lined curve in Figure 3 depicts the remaining proportion at time t of a CO_2 pulse generated at time t = 0 from the combustion of an amount of fossil fuels (oil) in the no-harvest scenario. The left axis shows the effect on RF in kW, while the right axis shows the corresponding amount of carbon in tC. The unbroken, grey curve shows the net effect of the pulse emission caused by combustion of the harvest, together with the effect of the release of carbon due to decomposition of dead organic matter left on the stand after harvest, as well as the stand's carbon capture due to regrowth after harvesting.

Figure 3. Illustration of the development of the effects of harvesting and no-harvesting on the amount of carbon in the atmosphere (also measured in radiative forcing on the left axis)



Next, consider the albedo effect. It was assumed that clearcutting of a considered stand of 1 ha results in an immediate rise in albedo. This was labeled $\Delta \mathrm{RF}_{\mathrm{albedo}}(0)$ using kW as the unit. The albedo effect is gradually reduced as regrowth takes place. Hence, the albedo t years after harvesting was assumed to be

$$\Delta RF_{albedo}(t) = (1-\delta_{\mathrm{albedo}}) \cdot \Delta RF_{albedo}(0). \tag{3}$$

In practice, the albedo effect from clearcutting a site varies significantly depending on the exact site considered. The parameters in (3) are based on Cherubini *et al.* (2012), more specifically their Norwegian cases. The parameter δ_{albedo} was set to 0.045, and $\Delta RF_{albedo}(0)$ to 135.1 kW/ha and 168.6 kW/ha in the cases without and with extraction of aboveground residues from the stand, respectively. These two cases are different, since Cherubini *et al.* (2012) found that the reflection is larger from a stand if the residues are removed from the stand than in the case where residues are left on the forest floor. In the case where residues were also harvested, the time profile of the albedo effect of harvesting is shown by the double-lined unbroken curve in Figure 3.

Calculation of CO_2 emissions from the combustion of biomass

As mentioned, harvesting at stand age 100 years was assumed to yield 194 m^3 of wood when only the trunks were harvested. A case was also considered in which approximately 75 percent of tops and branches were harvested together with the stems. Following Holtsmark (2014), tops and branches are assumed to constitute 17 percent of the trees' biomass. Hence, the collected harvest residues are assumed to amount to 53m^3, and a total of 247 m^3 of wood is harvested in that case. As 1 m^3 of wood is assumed to contain 200 kg C, this means that combustion of the harvest releases 38.8 tC and 49.3 tC in the case without and with the collection of residues, respectively.

The assumption made here, i.e., that the entire harvest is used for energy purposes, is common in the literature, but it should nevertheless be discussed. Typically, 20 – 30 percent of the stems are used as building materials or furniture. Moreover, a large proportion of the harvest is usually used as input in the pulp and paper industry. Although almost all the biomass that is used in the pulp and paper industry can be assumed to be combusted within less than a year after harvesting, it might seem unrealistic to study a case where 100 percent of the biomass is used for energy purposes.

There are reasons for this choice, however. The point of departure for the analysis is possible large-scale increased harvesting aimed at expanding the supply of biomass for energy purposes. Different kinds of subsidies are likely tools for achieving such expansion, and a number of subsidies are already in place. For example, the fact that CO_2 emissions are not included in the EU-ETS is an implicit subsidy that has effect in Europe. These subsidies lead to increased demand for wood fuels, followed by higher wood prices and thereby increased harvesting. However, there are few reasons to believe that increased harvesting will lead to increased use of wood in buildings and furniture, etc. Instead, higher wood prices as a result of the abovementioned policies promoting increased use of bioenergy are likely to have the opposite effect. If the harvest level increases while, at the same time, demand for biomass for construction purposes remains unchanged, or is perhaps lower, it is appropriate to make the assumption that the whole harvest is used for energy purposes. It is essential here to keep in mind that the purpose of the study is not to analyze the climatic effects of forestry as such, but rather the climatic effects of increased harvesting to increase the supply of bioenergy.

Results

Estimates of GWPbio

Table 1 shows the estimates of GWP_{bio}. Two cases are shown, one with no collection of harvest residues and one with the collection of 34 percent of the residues. A proportion of 34 percent of the residues was chosen because that would represent a case in which all branches and tops were harvested together with the trunks.

Table 1. GWP_{bio} for the cases with and without collection of residues

Time horizon	20	100	500
Case with no collection of residues			
Bio CO_2	1.92	1.59	0.32
Albedo	-1.01	-0.49	-0.15
Net effect	0.91	1.10	0.16
Case with collection of residues			
Bio CO_2	1.54	1.20	0.24
Albedo	-0.93	-0.45	-0.14
Net effect	0.62	0.75	0.10

In both the two cases presented in Table 1, the first line shows the estimates of GWP_{bio} before taking albedo effects into account. Hence, these numbers correspond to the GWP_{bio} estimates presented in Holtsmark (2014). Because an improved model for the decomposition of dead organic matter was applied in the present study, the estimates are slightly different from the estimates presented in Holtsmark (2014).

The second rows in the two cases presented in Table 1 show the albedo effect. It is negative, because harvesting increases the reflectivity from the stand and cools the climate. Note that there is a slight difference in the albedo effect in the cases with and without the collection of residues. As mentioned, I adopted the assumptions made by Cherubini *et al.* (2012) that the collection of residues increases the reflectivity from the forest ground. At the same time, however, residue collection increases the emission pulse from combustion of the harvest. Here, it is important to keep in mind that GWP_{bio} is a relative (unit-based) measure of warming. In the case in which residues are harvested, the absolute warming effect of the emission pulse caused by combustion is greater than in the case without residue collection. Hence, although the absolute albedo effect is larger in the case with collection of residues, the relative albedo effect (relative to the amount of biomass harvested) is smaller.

Row three in the two cases presented in Table 1 shows the net effect when the cooling effect of increased albedo is subtracted from the warming effect of CO_2. In the case without subsidies, the GWP_{bio} is slightly higher than 1, with a time horizon of 100 years, while it is below 1 in the case with residue collection.

If a time perspective of 500 years is found to be more relevant than the 100 years discussed above, the results will be significantly more in favor of wood fuels. For example, in the case with no residues harvested, and with a 500-year time horizon, GWP_{bio} was found to be 0.10 and 0.16, respectively, in the cases with and without the collection of residues; see Table 1.

As mentioned in the introduction, the results presented here and in Holtsmark (2014) differ significantly from results presented in earlier studies. For example, Table 1 in Cherubini *et al.* (2012) shows net GWP_{bio} factors of 0.20 and 0.12 in very similar cases, when a 100-year time horizon was applied. However, as discussed in further detail in Holtsmark (2014), Cherubini *et al.* (2012) applied a simplified model of a forest stand of the type used in Guest *et al.* (2012), see Figure 1. It would therefore be valuable to check how the model performs if it is simplified in accordance with the simplifications made by Cherubini *et al.* (2012). That would mean that an abrupt halt in forest growth when the stand age reaches 100 years must be assumed. Moreover, in the no-harvest reference scenario, the forest stand's carbon stock should be kept fixed. Finally, it must be assumed that no accumulation of dead organic matter and no release of carbon from the soil take place after harvesting.

Table 2 shows the simulation results if the model of the forest stand applied in this paper were simplified in these ways. The albedo effects did not change compared to Table 1, but the CO_2 effects are smaller, painting a picture that is much more in favor of bioenergy, as in Cherubini *et al.* (2012). This illustrates the importance of using a model of a forest stand that includes the dynamics of all the main carbon pools, as well as using a realistic no-harvest reference scenario when assessing the climatic effects of bioenergy.

Table 2. GWPs for the cases with and without collection of residues, when the model of the forest stand was simplified along the lines applied by Cherubini *et al.* (2012)

Time horizon	20	100	500
Case with no collection of residues			
Bio CO_2	1.25	0.65	0.11
Albedo	-1.01	-0.49	-0.15
Net effect	0.23	0.15	-0.04
Case with collection of residues			
Bio CO_2	1.11	0.55	0.09
Albedo	-1.00	-0.49	-0.15
Net effect	0.12	0.06	-0.06

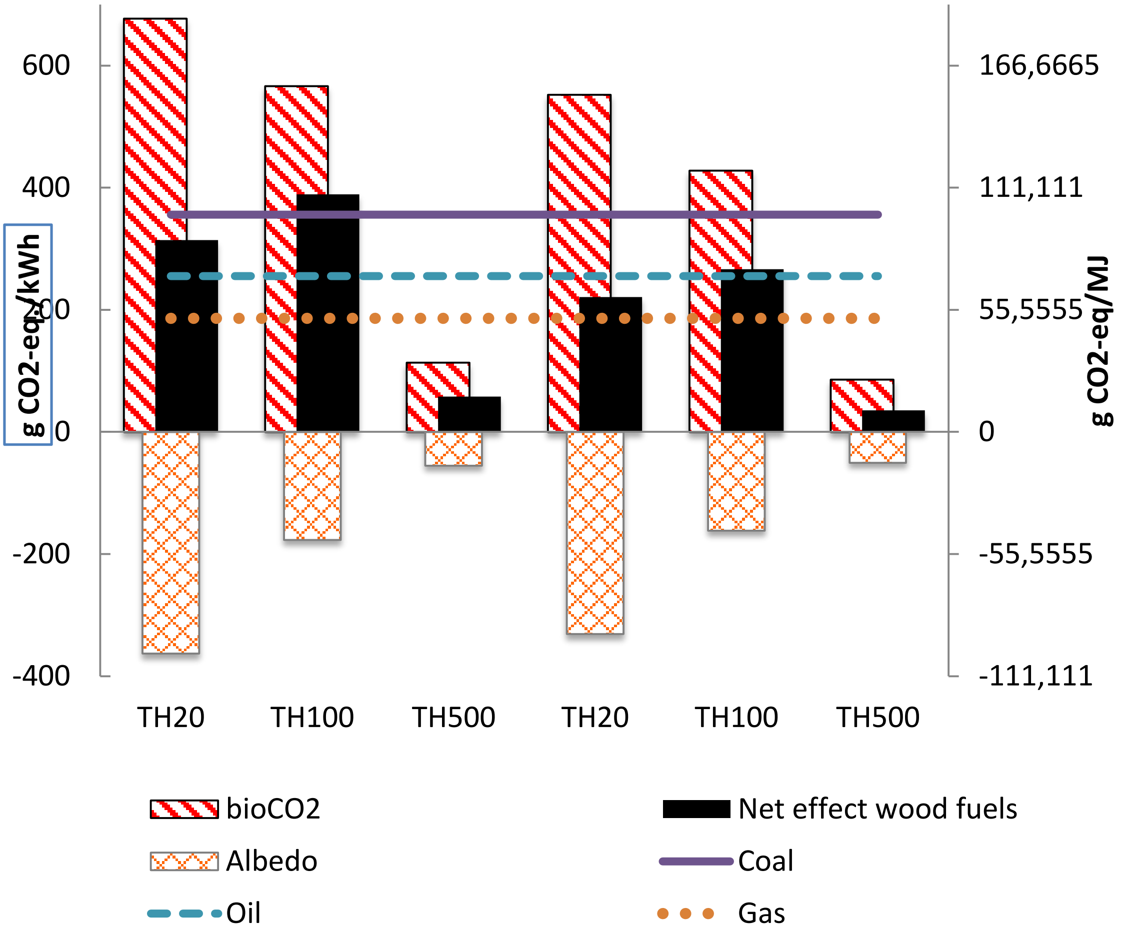
Comparison with fossil fuels

The numbers in Table 1 show the net warming effect of CO_2 emissions from the combustion of biomass when it is taken into account how harvesting changes the dynamics of the different carbon pools of the considered forest stand, as well as the lifetime of CO_2 in the atmosphere. However, for a complete comparison of bioenergy and fossil fuels, it should also be taken into account how much CO_2 is emitted per kWh that is produced. We report on such a comparison in the following.

For the purpose of this comparison and as a benchmark, we assumed that both biomass and fossil fuels are combusted with 100 per cent efficiency. In practice, combustion will never be 100 percent efficient. For example, a power plant typically has a combustion efficiency of around 40 percent when the energy source is coal or wood pellets. An efficient modern gas power plant, on the other hand, is more likely to have combustion efficiency as high as 55 percent. In other words, there are large variations with respect to combustion efficiency, depending on the exact technology used. If the results reported in this article are applied to certain technologies where the efficiency ratios are different for the combustion of biomass compared to fossil fuels, the emission ratios should be adjusted accordingly. Hence, the results presented here are a starting point for such comparisons.

The energy generated by the combustion of wood depends on the moisture content, which in this case was assumed to be 15 percent. With 100 percent efficiency, the combustion of wood will then yield approximately 2050 kWh/m3 (Holtsmark 2012a). With an estimated carbon content of 200 kg C/m3, the emission ratio will be 358 g CO_2/kWh with 100 percent combustion efficiency. By comparison, and as a benchmark, average emissions of 356 g CO_2/kWh were assumed for coal, 255 g CO_2/kWh for oil, and 186 g CO_2/kWh for gas, when combustion is 100 percent efficient.

Figure 4. The global warming potentials of wood fuels in g CO_2-equivalents/kWh, with the warming potentials of fossil fuels included as benchmarks. As regards both biofuels and fossil fuels, 100 percent combustion efficiency is assumed. The hatched columns show the net warming effect of harvesting due to its influence on the carbon cycle. The cross-hatched columns show the albedo effect of harvesting, while the black columns show the net effect on warming when both the albedo effect and effects on the carbon cycle are taken into account



There are also large variations in energy losses and energy consumption in connection with both the harvesting and processing of wood fuels, as well as the production, refining and distribution of fossil fuels. The energy losses in connection with the production of liquid biofuels from wood are particularly large. Nevertheless, to make the analysis as simple and transparent as possible, emissions relating to harvesting and processing are not included in the calculations presented in this paper. This also applies when I consider fossil fuels. Again, the results serve as a transparent basis for comparison. If information were available about energy losses related to the degree of combustion efficiency and energy use related to processing etc., the results reported here should be supplemented to provide more specific policy advice about different technologies.

Figure 4 shows the global warming effect of wood fuels in gCO_2-equivalents/kWh, with the warming impacts of fossil fuels included as benchmarks. The three left-hand groups of columns represent the case *without* collection of any residues, while the three right-hand groups of columns represent the case *with* collection of 75 percent of tops and branches in addition to the stems. Three different time horizons were considered: 20 years, 100 years, and 500 years.

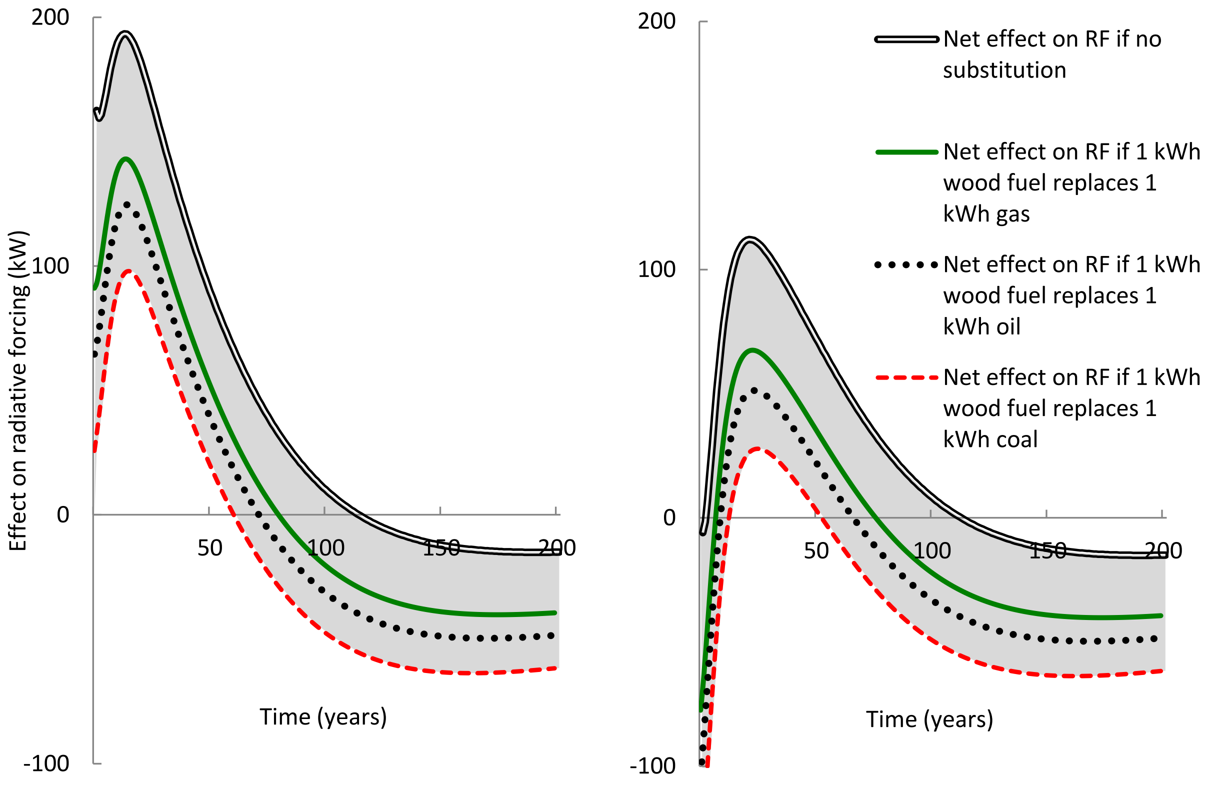
From a single harvest approach to a permanent harvesting approach

In the previous sections, we reported the results from simulations of harvesting of a single stand at time *t*=0. However, the discussion of the climatic consequences of using bioenergy concerns whether society, *on a long-term basis,* should increase its use of bioenergy. That would mean harvesting not only in year *t*=0, but in all subsequent years as well. A “landscape approach” should be taken to analyze a policy scenario of this type. For illustrative purposes, a forest consisting of 100 stands is considered. Each stand in this forest has exactly the same properties as the stand that was analyzed in the previous sections; see Figure 2. In the following, however, it is assumed that the stands’ age (years since last harvest) varies as follows. The age of stand number 1 is 100 years in year *t*=0 and it is ready for harvesting. The age of stand number 2 is 99 years at time *t*=0, and it will thus be ready for harvesting in year *t*=1, and so forth. Hence, in year *t*=99 the last stand is ready for harvesting, while in year *t*=100 stand number 1 is again mature and ready for harvesting, and a complete new rotation will follow over the next century.
Before analyzing the landscape approach, we need to return to the single harvest approach described in

Figure 5. This diagram explains the consequences of harvesting stand number 1 in year *t*=0. First, consider the double-lined curves in Figure 5 (which corresponds to the solid black curve in Figure 3). These curves show the time profile of the net effect of harvesting on RF if an increased supply of bioenergy does not lead to any reduction in the consumption of fossil fuels.

This is a limiting and unlikely case. It is more likely that an increased supply of bioenergy will lead to lower energy prices, which, in turn, will lead to reduced supply, and thus also to reduced consumption of fossil fuels. Exactly what types of energy consumption will be reduced when the bioenergy supply is increased, and to what extent, depends on the elasticity of supply and demand in the energy markets (Hutchinson *et al.* 2010). The difficult task of estimating supply and demand in the energy markets goes beyond the limits of this work. However, this work endeavors to provide information about the degree of uncertainty at this point by reporting both the limiting cases where 1 kWh of wood fuels replaces 1 kWh fossil fuels and the limiting case with no substitution of fossil fuels at all. Since both no substitution and full substitution on a 1 kWh to 1 kWh basis are unlikely cases, the most likely outcome is somewhere in-between these limiting cases. In the limiting cases with full substitution, the replacement of coal, oil, and gas are considered as three separate cases.

Figure 5. A single harvest event – the oil substitution case. The effect on RF if a stand of age 100 years, as described in Figure 2, is harvested in year t=0. 75 percent of the tops and branches are harvested together with the stems. The entire harvest is used for bioenergy. In the reference scenario, the stand is not harvested. Instead, an amount of fossil oil provides the same energy supply (in kWh). The left-hand diagram shows the case without any albedo changes, while a significant increase in albedo is assumed in the right-hand diagram



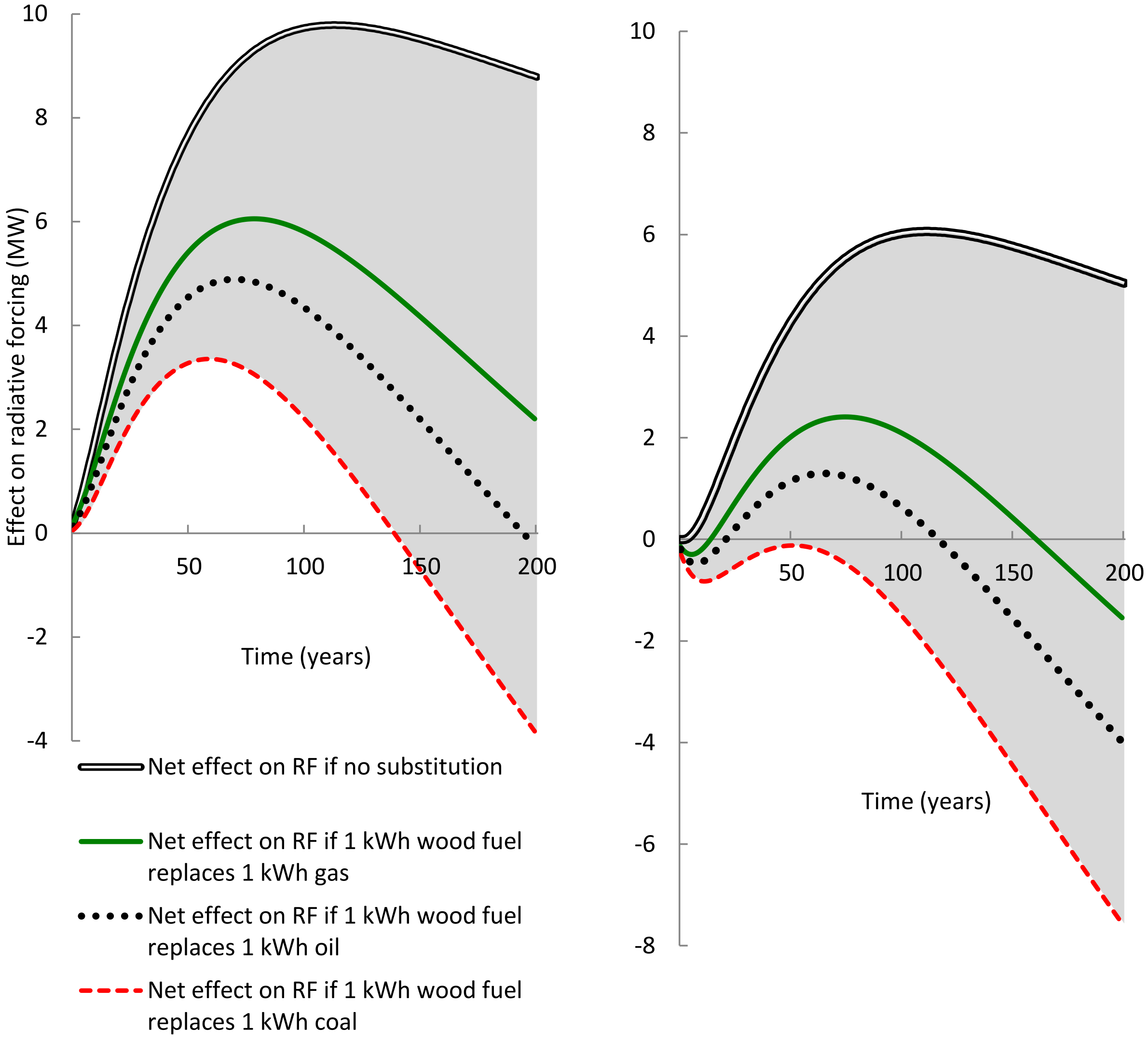
The single-lined broken curves in Figure 5 show the limiting case where each kWh of biofuels replaces one kWh of coal. The single-lined solid curves and the dotted curves show the case where 1 kWh of wood fuel replaces 1 kWh of gas and oil, respectively. Taking a static approach to the energy markets, these three limiting cases with full substitution would represent a case with a horizontal supply curve for fossil fuels (perfectly elastic supply). However, it is unlikely that the supply of fossil fuels is perfectly elastic, but rather that it is increasing in price. That would mean less substitution, and the final effect of harvesting on RF is in-between the three limiting cases on the optimistic side (with full substitution) and the limiting case on the pessimistic side (with no reduction in fossil fuel consumption; see the double-lined curve in Fig. 5). If the supply of fossil fuels is very elastic, the result is close to the double-lined curves, while it is closer to the lower curves if the fossil fuel supply is relatively non-elastic.

Comparing the right and left-hand diagrams in Figure 5, we see that the results are identical in the long term, but different in the short term. The differences in the short term appear because the right-hand diagram assumes a significant albedo effect of harvesting, while the left-hand diagram does not. In the albedo case, an immediate net cooling effect was assumed. A period of net warming follows after that, also when substitution is taken into account. However, after 55 – 110 years, there will again be a net cooling effect because the stand has regrown. Note that there will be a cooling effect in the long term even in the case with no substitution of fossil fuel consumption. This is because part of the released biogenic carbon has been absorbed by the sea and the terrestrial biosphere. Hence, in the long term, the net effect of the single harvest event is reduced CO_2 concentration in the atmosphere, also in the case where the increased supply of wood fuels does not replace any fossil fuel consumption.

To capture the true effects of a permanent increase in the use of bioenergy, the multiple harvest approach is considered in the following. This means that harvest events take place every year from *t*=0 onwards. As already mentioned, each stand has the properties described in Figure 2. Note, however, that, here, the stand described in Figure 2 is harvested only once, and not repeatedly after 100 years. This is to make the exposition as transparent as possible. Note also that it is irrelevant to the results whether the stands that are harvested in rotations number two, three, and so forth, are the same stands as the 100 stands that were harvested in the first rotation. The key point is that, every year, a new stand reaches the age of 100 years and is harvested (in the harvest scenario).

Figure 6 shows the results of the multiple harvesting approach. Again, the right-hand diagram is based on a significant albedo effect of harvesting, while the left-hand diagram does not include such an effect.

Figure 6. **The multiple harvest (landscape) approach. The effect on RF if, every year from t=0, one stand of age 100 years, with properties as described in Figure 2, is harvested. Most (75 percent) of the tops and branches were assumed to be harvested together with the stems. The entire harvest was used for bioenergy. In the reference scenario, the stands are not harvested. Instead, fossil fuels provide the same energy supply (in kWh). The left-hand diagram shows the case without any albedo changes, while a significant increase in albedo is assumed in the right-hand diagram**



First, note that using the multiple harvesting (landscape) approach leads to a significantly different outcome from the single harvest (stand level) approach. Without substitution of fossil fuels (the double-lined curves), there is a warming effect in the whole time span shown (200 years). Moreover, as reported in Holtsmark (2013a), Figure 3, there will be a permanent warming effect if no substitution of fossil fuels takes place.

When there is substitution of fossil fuels, the results are less clear. First, consider the case without albedo effects (the left-hand diagram). If there is full substitution in the sense that 1 kWh of wood fuels replaces 1 kWh of coal, there will be an initial period of 140 years with net warming. This time span is often called the payback time of the carbon debt. If wood fuels replace oil or gas, the payback time is significantly longer than in the case of coal, see Figure 6.

Next, consider the case with albedo effects (the right-hand diagram in Fig. 6). In that case, there will be an immediate cooling effect after time t=0, at least if there is full substitution. Furthermore, if wood fuels fully replace coal, there will not be any period of net warming at all. However, if the substitution effect is smaller, the result will be somewhere in-between the broken and the double-lined curves, and there might consequently also be net warming in the coal case.

If wood fuels replace oil or gas, there will also be significant periods of warming in the most optimistic cases with full substitution. However, it is more likely that the degree of substitution will be smaller, leading to a less favorable effect of harvesting that lies somewhere in the grey area between the broken and solid curves.

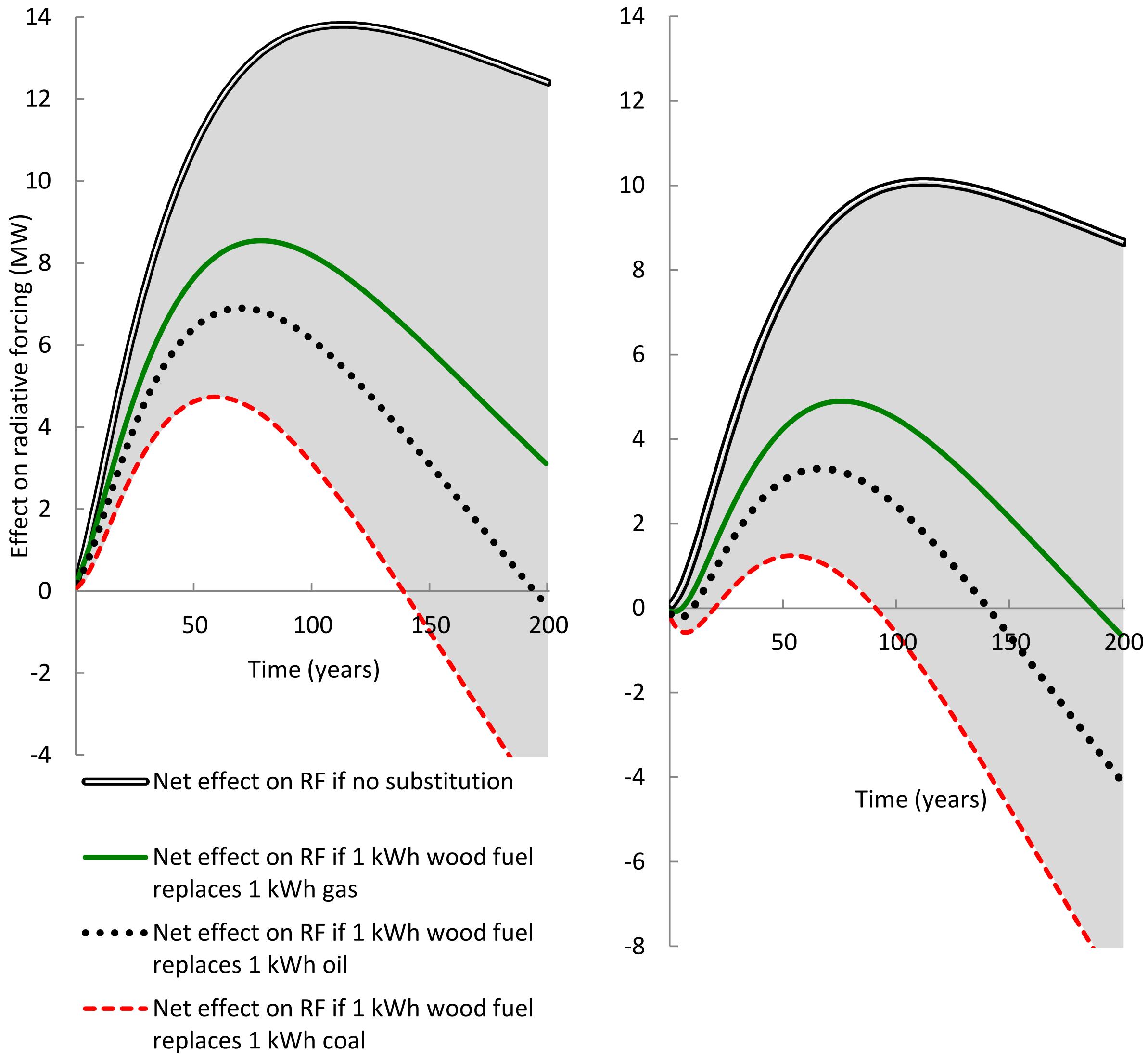
Finally, a case is considered in which the climate sensitivity of CO_2 is 4.5 C, not 3 C, as assumed in all the simulations presented so far. The results are presented in Figure 7.

The left-hand diagram in Figure 7 shows the case without any albedo changes, while the right-hand diagram shows the case where harvesting leads to increased albedo. Note that a climate sensitivity of 4.5 °C is likely to lead to significantly shorter winter seasons with snow cover, which means that the albedo effect of harvesting is likely to be notably weakened over time. This weakening of the albedo effect is not taken into account here, which means that the simulations shown in Figure 7 are likely to overstate the cooling effect of albedo some decades into the future, especially in the case with a climate sensitivity of 4.5 °C.

Nevertheless, comparing Figures 6 and 7 shows how sensitive the net warming effect of harvesting is as regards the relationship between the warming effect of CO_2 and the cooling effect of increased albedo. If the climate sensitivity of CO_2 is at the high end of the confidence interval presented by the

IPCC (1.5 – 4. 5 °C), there are no clear climate gains from bioenergy in the first century after the first harvesting, even with the most optimistic assumptions about the substitution of bioenergy for coal. In addition, if the shorter period with snow cover that will be a reality with high climate sensitivity had been taken into account, the biofuels scenario would have been even less favorable.

Figure 7. The case with a climate sensitivity of CO_2 of 4.5 °C. The effect on RF if, every year from t=0, one stand of age 100 years, with properties as described in Figure 2, is harvested. Most (75 percent) of the tops and branches were assumed to be harvested together with the stems. The entire harvest was used for bioenergy. In the reference scenario, the stands are not harvested. Instead, fossil fuels provide the same energy supply (in kWh). The left-hand diagram shows the case without any albedo changes, while a significant increase in albedo is assumed in the right-hand diagram



Discussion

In the past few years, a number of studies have applied the GWP concept to quantify the warming impact of combustion of biomass. This paper adopted the method of earlier studies that used the GWP concept, but, as in Holtsmark (2014), an improved model of the forest stand was applied, taking the dynamics of the stand's different carbon pools into account. In addition, the present paper further improved the method applied by Holtsmark (2014) by taking albedo changes from harvesting into account in addition to using an improved model for the decomposition of dead organic matter. Cases both with and without albedo effects were considered, however.

When the albedo effect is not taken into account, the estimates of GWP_{bio} are almost identical to the results found in Holtsmark (2014). Hence, through the inclusion of an improved model for decomposition of dead organic matter, the conclusions in Holtsmark (2014) are confirmed. The GWP_{bio} of biomass from a slow-growing forest was found to be above 1 if the albedo effects of harvesting are insignificant (Table 1), in contrast to earlier studies of GWP_{bio}, such as Cherubini *et al.* (2011b, 2012), Bright *et al.* (2012), Guest *et al.* (2012), and Pingoud *et al.* (2011), who all presented estimates of GWP_{bio} in the interval 0.34 – 0.62 when slow-growing forest stands were considered. Holtsmark (2014) provided detailed explanations of these disagreements.

When albedo effects are included in the calculations, the GWP_{bio} estimates become significantly lower. When residues (tops and branches) are collected together with the stems, the GWP_{bio} estimate drops to 0.75, when a time horizon of 100 years is applied. In the case without the collection of any residues, GWP_{bio} was found to be 1.1. Although lower than the estimates of GWP_{bio} found in Holtsmark (2014), this is significantly higher than the GWP_{bio} estimated by Cherubini *et al.* (2012), whose GWP_{bio} estimates were close to zero when albedo effects were taken into account.

To explain the discrepancies, a simplified forest stand model was simulated (Table 2). The simplifications of the model were in accordance with the simplified model used by Cherubini *et al.* (2012), including no accumulation of naturally dead organic matter, an unlikely abrupt stop in forest growth when the stand age reaches 100 years, no accumulation of carbon in the stand in the no-harvest scenario, and no release of soil carbon after harvesting. This exercise yielded a GWP_{bio} estimate of 0.06 (a time horizon of 100 years), which is in good agreement with the results of Cherubini *et al.* (2012), see Table 2. This exercise demonstrated that the low GWP_{bio}-estimates reported by Cherubini *et al.* (2012) are artifacts of their simplified model of the forest stand and the lack of a realistic baseline scenario.

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