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IS WOODY BIOENERGY CARBON NEUTRAL? A COMPARATIVE ASSESSMENT OF EMISSIONS FROM CONSUMPTION OF WOODY BIOENERGY AND FOSSIL FUEL

Running title: Is woody bioenergy carbon neutral?

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ABSTRACT

Under the current accounting systems, emissions produced when biomass is burnt for energy are accounted as zero, resulting in what is referred to as the "carbon neutrality" assumption. However, if current harvest levels are increased to produce more bioenergy, carbon that would have been stored in the biosphere might be instead released in the atmosphere. This study utilizes a comparative approach that considers emissions under alternative energy supply options. This approach shows that the emission benefits of bioenergy compared to use of fossil fuel are time-dependent. It emerges that the assumption that bioenergy always results in zero GHG emissions compared to use of fossil fuels can be misleading, particularly in the context of short-to-medium term goals. While it is clear that all sources of woody bioenergy from sustainably managed forests will produce emission reductions in the long term, different woody biomass sources have various impacts in the short-medium term. The study shows that the use of forest residues that are easily decomposable can produce GHG benefits compared to use of fossil fuels from the beginning of their use and that biomass from dedicated plantations established on marginal land can be carbon neutral from the beginning of its use. On the other hand, the risk of short-to-medium term negative impacts is high when additional fellings are extracted to produce bioenergy, when the proportion of felled biomass used for bioenergy is low, and when land with high C stocks is converted to low productivity bioenergy plantations.

The method used in the study provides an instrument to identify the time-dependent pattern of emission reductions for alternative bioenergy sources. In this way, decision makers can evaluate which bioenergy options are most beneficial for meeting short-term GHG emission reduction goals and which ones are more appropriate for medium to longer term objectives.

1 INTRODUCTION

Increasing use of renewable energy is a key EU strategy for reducing its greenhouse gas (GHG) emissions and contributing to policy objectives within the next 40 years to maintain the global temperature rise below 2°C. A substantial share of the total renewable energy needed to meet EU targets will come from biomass. According to projections on the deployment of renewable energy sources, energy from solid biomass and organic waste will constitute 58% of the total renewable energy generation in 2020 (140 Mtoe[1] of 240 Mtoe) (Ragwitz *et al.* 2009).

Under the current UNFCCC accounting systems, carbon dioxide (CO_2) emissions produced when biomass is burnt for energy are not accounted for in the energy sector, resulting in what is referred to as the "carbon neutrality" assumption (UNFCCC 2006). The convention is based on the assumption that the carbon (C) released when biomass is burnt will be recaptured by plant regrowth and that any excess of releases over regrowth will show up as a loss of C stock and will be accounted for in the land use sector. However, in practice, the current accounting system for the land use sector is incomplete. It was designed for a system in which all nations account for all C stock changes from land use, whereas only a limited set of countries currently account for a limited number of C stock changes.

Additional considerations arise from two issues. First, while in the case of annual crops emissions and regrowth occur within one year, there is a time delay between emissions and subsequent regrowth when woody biomass is burnt. Second, current harvest levels might be increased, for instance, to achieve renewable energy targets (Mantau *et al*. 2010). In this case, the overall C stock of forests might be lower than

[1] Mtoe = million tonnes of oil equivalent

the C stock in the non-bioenergy scenario for the entire period when forest management is intensified, even in forests that are being sustainably managed. Where harvests are increased, C that would have been stored in the biosphere is burnt instead and released as CO_2 into the atmosphere. When these C stock changes are included in the emission profile of bioenergy, the question arises as to whether a nation will have more net emissions within the time frame of climate change policies aiming to achieve the 2° C target if the biomass is extracted and used for energy or if fossil fuels are used.

This study builds up on research developed in the 1990's showing that emissions reductions that are achieved by substituting bioenergy for fossil fuels use are time-dependent, i.e. they change over time and that bioenergy is not always carbon neutral (Schlamadinger *et al.* 1994, 1995, 1997; Schlamadinger and Marland1996). Recent papers have confirmed those results, showing that the benefits of bioenergy use change according to the time frame that is considered. Initially these studies considered a specific bioenergy source removed from a single stand and a one-time removal (Palosuo *et al.* 2001). More recent studies have started to discuss the effect of adopting a landscape rather than a stand-level view (Walker *et al.* 2010) and to compare different bioenergy sources (McKechnie *et al.* 2011; Repo *et al.* 2011). Other studies have used metrics that express the time-dependent emissions of bioenergy in terms of global warming potential (Cherubini et al. 2011a, b; Sathre and Gustavsson 2011). The assumptions and factors included differ among the studies, but the general conclusions are in agreement in stating that bioenergy is not always carbon neutral.

This study contributes to the discussion by comparing time-dependent emission benefits from different wood sources, thus helping to identify which bioenergy sources might be more beneficial to achieve near-term emission reduction targets. The study uses selected, illustrative examples to achieve this objective, showing the benefits over time of using wood from residues, additional fellings and new plantations.

2 METHOD

The benefits in terms of GHG emission reductions produced over time by using woody biomass for energy are assessed by comparing the bioenergy system to the fossil fuel system that is replaced.

Emissions in both systems can be classified as:

- Production chain emissions, i.e. the emissions released to produce, transport, convert and distribute the fuel
- Resource *consumption emissions*: the carbon (C) released when the mass of fuel – either biomass or a fossil fuel – is burnt.

This paper focuses only on the resource *consumption emissions* of different energy supply systems. In the case of bioenergy, these emissions are usually ignored under the assumption of carbon neutrality. In this study a metric is defined that expresses benefits in terms of emission reductions resulting from using biomass rather than fossil fuel sources for energy.

As a first step biomass *consumption emissions* are determined:

A. Biomass *consumption emissions,* i.e., emissions that are attributable to burning biomass to replace some fossil energy, are calculated as the difference between the forest C stock under the bioenergy scenario and the forest C stock under the fossil fuel scenario (i.e. when biomass is not extracted for bioenergy) at a given point in time:

[1] $$Ec_B(t) = (BC_B(t) - BC_{FF}(t)) * 44/12$$

$Ec_B(t)$: *consumption emissions* from biomass at time t if a bioenergy system is implemented, (tCO_2)

$BC_B(t)$: forest C stock under the bioenergy scenario at time *t* (tC)

$BC_{FF}(t)$: forest C stock under the fossil fuel scenario at time *t* (tC)

The forest C stock in both scenarios includes the C in tree biomass, litter and soil organic matter. This equation enables identification of the changes in forest C stocks attributable to bioenergy over time even in net-growing forests (Figure 1). In practical terms, these emissions are the difference between C stocks under two different management regimes, one more intensive than the other. This stock difference usually decreases over time because growth rates differ under the two management regimes, with net annual increment usually higher under more intensive management. Other factors that might influence C stock levels, such as climate change and change of natural disturbance risk, are not considered in this study.

As a second step fossil fuel *consumption emissions* are determined:

B. Fossil fuel *consumption emissions* are equal to the C released when fossil fuel is burnt in the fossil-fuel scenario (baseline). In the bioenergy scenario these emissions are avoided because fossil fuel is replaced by biomass. It can be assumed that there is a total loss of C to the atmosphere when fossil fuel is burnt, i.e., no increase of fossil C stocks occurs in a time period of relevance due to the very long time required to create fossil fuel stocks. Similarly to the equation used for bioenergy emissions, the fossil fuel *consumption emissions* at time *t* ($Ec_{FF}(t)$, tCO_2) are equal to:

[2] $$Ec_{FF}(t) = (FC_{FF}(t) - FC_B(t)) * 44/12$$

$FC_{FF}(t)$: fossil C stock under the fossil fuel scenario at time t (tC)

$FC_B(t)$: fossil C stock under the bioenergy scenario at time t (tC)

$FC_{FF}(t)$ decrease over time more than $FC_B(t)$ by an amount equal to the fossil carbon that is replaced in the bioenergy scenario. Therefore, at year *t*, the fossil *consumption emissions*, $Ec_{FF}(t)$, are equal to the cumulative amount of fossil carbon burnt up to that year.

As a third step resource *consumption emissions* from the two scenarios are compared. The comparison of the biomass *consumption emissions* [1] with fossil fuel *consumption emissions* [2] determines the impact, in terms of emissions, of using biomass instead of fossil carbon for energy over time, production chain emissions excluded.

This impact of biomass use over time can be expressed as a factor. Carbon neutrality factors were first defined by Schlamadinger and Spitzer (1994) to quantify the extent to which use of biomass reduces emissions compared to a replaced fossil fuel over time. The factor CN(t) could cover both production chain and what we consider as *consumption emissions*, and is defined as follows:

[3] $$CN(t) = \frac{E_{FF}(t) - E_B(t)}{E_{FF}(t)} = 1 - \frac{E_B(t)}{E_{FF}(t)}$$

Where:

$E_{FF}(t)$: emissions from the fossil fuel system at year *t*

$E_B(t)$: emissions from the bioenergy system at year *t*

This definition of CN factors leads to the following (Figure 2):

a) *CN* <0 where bioenergy system emissions are higher than those in the fossil fuel system.

b) *CN* =0 where bioenergy system emissions equal those of the reference system.

c) $0<CN<1$ the bioenergy system produces less emissions than fossil fuels (e.g. if CN=0.6, bioenergy produces 60% less emissions)

d) CN =1 if the bioenergy system produces zero net emissions

e) CN >1, when the bioenergy system produces a C sink in the biosphere in addition to 100% emission reductions compared to the fossil fuel .

Under this system, a CN = 1 corresponds to the basic concept imbedded in viewing bioenergy as "carbon neutral". Under this definition, at points in time when a bioenergy system has a CN of 1, use of bioenergy reduces emissions by 100% compared to use of a fossil fuel.

Whereas a comprehensive analysis to assess the GHG emissions of bioenergy compared to fossil fuel should include production chain emissions, this study focuses only on the impact of resource *consumption emissions*. Therefore, if equation [3] is confined only to resource *consumption emissions*, it becomes equal to:

[4] $$CN(t) = \frac{Ec_{FF}(t) - Ec_B(t)}{Ec_{FF}(t)} = 1 - \frac{Ec_B(t)}{Ec_{FF}(t)}$$

2.1 <u>Case studies</u>

To illustrate the emission reduction produced by the use of different biomass sources, we present three illustrative examples:

1. Additional fellings from a managed forest
2. Extraction of harvest residues from a managed forest
3. Bioenergy from new tree plantations

It is assumed that each biomass source will be used to substitute coal, oil or natural gas. For purposes of the calculations in this paper, it is assumed that the coal and bioenergy systems have the same conversion efficiency and the same CO_2 emissions per unit of energy produced (Schlamadinger et al. 1995). This is approximately the case where biomass is used to replace coal for electricity. It is also assumed that oil causes about 20% less C emissions per unit energy than coal, while natural gas produce about 40% less emissions than coal (Schlamadinger et al. 1995; Sathre and Gustavsson 2011). Therefore, where biomass is used to replace, for example, natural gas, benefits are lower, or take longer to emerge.

In the following examples, a modified version of the GORCAM model is used to simulate the effects of a change in management or land use against a baseline scenario (http://www.ieabioenergy-task38.org/softwaretools/gorcam.htm).

For simplicity and comparability of results, changes of management scenarios in managed forests are simulated for a single type of forest. The example is a typical stand of Norwegian Spruce (*Picea abies*) in the Austrian Alps near Bruck an der Mur, Austria. The stand has a rotation period of 90 years. The growth curve of the spruce forest is derived from the Austrian yield table for "Spruce-Bruck/Mur", site class 10 (an index of site fertility equivalent to medium fertility) (Marschall 1975). Merchantable volume is converted to total aboveground and below biomass based on the allometric equations by Wirth *et al*. (2004). Litter inputs are calculated as a percentage of the living biomass, and the litter decay is estimated using a temperature, precipitation and litter quality model (Moore *et al*. 1999) (Table1). Climate parameters are derived from data collected at the station in Bruck an der Mur (mean annual temperature and precipitation: T=8.7°C, P=778 mm; ZAMG, 2009). The effect that climate change might have on the development of the C stocks in the baseline and in the bioenergy scenario is not included in this study. It is further assumed that the management changes entailed in the various biomass scenarios do not affect the natural disturbance regime. We consider a forest system of 90 ha of which one hectare is cut every year. The model assumes that prior to inauguration of the bioenergy scenario, there have been three complete rotations at harvest levels equal to those that occur under the baseline (e.g., no-bioenergy scenario). Changes of management to produce bioenergy occur after these three rotation periods. This assumption was introduced to simulate a change of management in forests that have been harvested in a steady manner for long periods.

In the following sections, the CO_2 emission reduction or increase of a specific biomass source compared to fossil fuels are represented by graphs that compare the biomass *consumption emissions* of bioenergy against the fossil fuel *consumption emissions* that would occur in the baseline. Graphs also show the development of the CN over time, i.e., the relative advantage of bioenergy against fossil fuel. The graphs represent the replacement of coal and natural gas, while replacement of oil, the intermediate case, is discussed in the text. Production chain emissions are neither shown nor considered in the calculation of the CN factors presented in this paper.

The results presented in this study on the relative advantage of bioenergy against fossil fuels are independent of the size (areal extent) of the forest or plantation considered. This is because a full rotation system, not a single stand, has been used in the modeling. As a consequence, if a change of management to produce bioenergy is promoted on larger areas, the biomass *consumption emissions* and the fossil fuel *consumption emissions* would increase in absolute terms, but the ratio between the two, expressed by the CN factor, would remain the same. The management in other forest areas not included in the bioenergy system remains unchanged both in the baseline and in the bioenergy scenario and therefore no C gain or loss from these areas are or should be included in the calculations.

3 RESULTS

3.1 Additional fellings

Increased demand for bioenergy could result in increased harvests from managed forests. According to a recent study (Mantau *et al*. 2010), the total demand for wood in Europe - consisting of the demand for material and energy uses - could increase by about 35% by 2020 compared to current levels. This demand could possibly be met domestically if the harvest levels are significantly increased beyond the current level of resource use. If the same additional amount of wood is taken out of the forests every year to provide a constant bioenergy supply, the forest C stock will develop differently than in a baseline scenario in which fellings are not increased and fossil fuels are burnt instead. Thus, it can be expected that the forest C stock in the bioenergy scenario will be smaller than in the baseline.

The following paragraphs illustrate a case study in which final fellings are increased beyond those in the baseline case to provide an annual wood supply for bioenergy. It is assumed that the entire increase in fellings is used to produce energy.

We consider two cases. In Case 1, a percentage of the net annual increment of the forest is removed. This simulates a sustainably managed forest, such as forests in Europe. The final fellings are increased from 60% (baseline scenario) to 80% of the forest net annual increment (Figure 3a). The objective of such management is to maintain sustainable management over time by always cutting less than annual growth. Under this management scheme, the absolute amount of biomass that is extracted will decrease over time. The reason for this is that if less than full annual growth is removed, the forest tends to mature, a condition that is characterized by increasingly lower growth rates. Nevertheless, under these circumstances, the difference in forest C stock between the two scenarios will eventually decrease, because of higher growth rates under the more intensive management regime.

Case 2 represents what happens when the priority is to guarantee a constant biomass supply. In this case, a constant amount of biomass has to be extracted from the forest over time. To simulate this type of management, we modeled a bioenergy scenario in which the biomass extracted is increased from the 60% baseline to 80% of the aboveground biomass in the harvested parcel. Under this scenario, the amount of harvested wood can initially be greater than the forest net annual increment although at some point a new equilibrium will be reached. When the new equilibrium is reached, the difference between the two management scenarios stays constant (Figure 3b).

Figure 4 shows the development of C stock changes in terms of CO_2 emissions from the forest ecosystem compared to the fossil fuel emissions over time. In both the cases where fellings are increased, the bioenergy system will produce more *consumption emissions* than the fossil fuel reference system for a long period. The use of bioenergy will start to produce some benefits, i.e. $CN \geq 0$, in:

- Case 1: after 175 years if coal is substituted and about 300 years if natural gas is substituted (Figure 4 - Case 1).
- Case 2: after about 230 years if coal is substituted and 400 years if natural gas is substituted (Figure 4 - Case 2).

Intermediate periods result if oil is substituted, i.e. about 230 years in Case 1 and 295 years in Case 2.

According to these case studies, increasing fellings in already managed forest with fairly long rotation periods may produce emission reductions compared to continued use of fossil fuels only in the long term. In the short-to-medium term (20-50 years) relevant for current climate policies, additional fellings might result in more CO_2 emissions than continued use of fossil fuels.

The main reason of the initial negative values of CN is that not all the biomass affected by additional fellings is used for energy. In the illustrated cases, it is assumed that all residues from the additional fellings are left in the forest. Therefore, biomass such as roots and aboveground residues is left in the forest to decompose, resulting in a loss of C stock that does not contribute to substitution of fossil fuels. Under these circumstances, the bioenergy system is less efficient than the fossil fuel system. If the efficiency of biomass use is increased, i.e., some portion of residues are used to produce energy instead of being left in the forest to decay, the period in which CN is negative is shortened. In Case 1, if the aboveground woody residues from the additional fellings are also removed to produce bioenergy, CN will be greater than zero after about 75 years instead of 175 years when coal is substituted and 200 years instead of 300 when natural gas is substituted.

This analysis does not take into account factors that could help maintain the total forest C stock unaffected under more intensive harvest regimes. Such factors could include management changes that improve the growth rate, such as fertilization, or lower disturbance risks from pests, storms and fires (Lindner *et al*. 2008). Management strategies in European forests could also combine increased fellings for bioenergy in certain areas with afforestation and nature-oriented management in others. The result would be a compensation of C losses in intensified management areas by an increase of stocks in other areas (Nabuurs *et al*. 2006).

3.2 Felling residues

One possible strategy to increase the biomass available for bioenergy is to collect forest residues usually left in the forest after harvest. Depending on the site, a certain amount of residues can be extracted without compromising soil fertility and therefore forest production (EEA 2006). If this amount of residues is utilized for bioenergy, emissions due to the management change are limited to the C stock changes in the dead wood, litter and soil pools (Schlamadinger *et al*. 1995; Palosuo *et al*. 2001, Repo et al. 2011).

When residues are left on the forest floor, they gradually decompose. Most of the C contained in their biomass is released over time into the atmosphere, but a small fraction is transformed into humus and soil carbon. Thus, when residues are burnt for bioenergy, carbon that would have been gradually released from the dead wood and litter pools as well as carbon that would have been stored in the soil is released immediately to the atmosphere. This produces a short term decrease of the dead wood and litter pools that is later translated into a decrease of soil carbon.

In our example of a spruce forest, woody residues previously left on the forest floor at the end of the rotation period are collected to produce bioenergy that substitutes for fossil fuel. In the baseline scenario 75% of aboveground biomass from fellings is used for forest products while the remaining 25% is left in the forest. According to allometric equations by Wirth *et al*. (2004), foliage accounts for an average of 11% of the aboveground biomass over a 90 year rotation period. It is assumed that the foliage is left is the forest in the bioenergy scenario to avoid loss of soil fertility. As a result, in the bioenergy scenario 14% of aboveground biomass left from felling operations (about 33 t ha^{-1} yr^{-1}) is removed to produce energy.

In this case, bioenergy starts to produce a benefit from almost the beginning when coal is replaced (Figure 5). At time 0 the *consumption emissions* due to use of the biomass equals the loss of C in the litter. Since an equal stock of fossil fuel is replaced, biomass *consumption emissions* are equal to the fossil fuel *consumption emissions* and the CN factor starts at 0. In the cases where bioenergy substitutes for oil and natural gas, it takes few years before bioenergy starts to produce some benefits compared to fossil fuels, 7 and 16 years respectively. With time the soil and litter C pools tends to reach a new equilibrium - lower than in the baseline -, while substitution of fossil fuel continues at a steady level. As a result, use of residues tends asymptotically toward 100% reductions compared to use of fossil fuels over time.

The results show that after 30 years the CN factor is about 0.6 in case of coal substitution and 0.3 in case of natural gas. This can be interpreted as meaning that use of biomass results in 60% or 30% less *consumption emissions* than use of fossil fuel by this point in time. In the case where coal is replaced, this could be correctly reflected in accounting by multiplying 60% of the bioenergy emissions by zero and assigning their full value (i.e., multiplying these CO_2 emissions by “1”) to the other 40 %. After 100 years, the CN factor is 0.76 to 0.85, i.e., bioenergy from residues produces only 15 to 24% of the emissions that would have resulted from use of coal or natural gas, respectively.

Other authors have come to similar conclusions. (Schlamadinger *et al.* 1995; Palosuo *et al.* 2001; Repo *et al.* 2011). Differences between their results and the results presented in this paper are a consequence of the different assumptions regarding management regimes and decomposition rates. As stated previously, this case study is based on data relevant to a Spruce forest in the Austrian Alps. Decomposition rates vary substantially for forests in other regions as well as by litter type. A review of litter decomposition rates shows that they increase with precipitation and temperature and are lower for coarse dead wood than for fine litter (Zhang *et al*. 2008). When the residues are coarse dead wood such as stumps, only a small fraction of the C decomposes in the forest within a year, e.g. 0.05 yr^{-1} for coarse dead wood (Palosuo *et al*. 2001). The rest remains as a C pool in the forest. When the stumps are removed and used for energy, their slower decomposition pattern must be taken into account. As a consequence, the CN of stumps used for bioenergy is likely to be significantly lower than CN values for fast decomposing residues after the same periods of time. Repo *et al*. (2011) report, for example, that emissions – production chain emission included – are 79% lower after 100 years of producing energy from combustion of branches instead of coal whereas emissions after 100 years are only 58% lower if stumps are combusted.

3.3 New plantations

Research studies show that marginal agricultural areas and degraded land could be used for afforestation or to grow energy crops, including short rotation plantations. Utilization of these areas for bioenergy has been advocated to reduce the risk of bioenergy competing with food demand and could contribute to rural development (Lu *et al*. 2009; Mangoyana 2009). It was estimated that 4.3 Million hectares (Mha) in the EU-27 have been set-aside or fallowed as a result of incentives. An additional 4.2 Mha are fallow without subsidies. If 35% of the area under incentives were put to use, 1.5 Mha of new forests or short rotation plantations could be used to produce bioenergy (Hetsch 2008).

Establishing new bioenergy plantations on lands with low initial C stocks, such as marginal agricultural land, has the clearest advantages in terms of emission reductions.

Such plantations consist of C stocks accumulated above those in the baseline, when the baseline is a situation in which land remains marginal agricultural land. Under these conditions, the C stock accumulated in the plantations in the bioenergy scenario represents removals of CO_2 from the atmosphere additional to those in the baseline. Therefore, when the accumulated carbon is burnt to produce energy, the C stock returns to levels similar to those in the baseline and in addition there is has a benefit from reduction of emissions from fossil fuels.

However, since plantations can be established not only on fallow lands or cropland but also on forested lands, plantations can produce either positive or negative C stock changes during land conversion. In each case, the changes of C stock entailed in the land conversion must be included in calculations.

Three cases are considered below: a case where land with a low C stock, such as marginal agricultural land, is converted to a tree plantation and two cases where a forest is cleared and replaced with a plantation. In all the cases it is assumed that the C stock in the baseline (marginal agricultural land or forest) would haveremained constant.

In Case A, where marginal agricultural land is converted, on site C losses are limited to soil C losses linked to site preparation. The temporary decrease of soil C stock, if any, is very soon recovered and followed by a net increase of soil carbon due to higher litter inputs from trees than from crops (Guo and Gifford 2002). Aboveground and belowground live biomass stock is also higher in the tree plantations than in agricultural land.

The combination of the increased C stocks and the use of bioenergy leads to CN factors greater than 1. In the beginning the CN is much greater than 1 because the sequestered carbon is much greater than the emissions from the fossil fuel system that is substituted. However, the initial sink tends to a constant value while the cumulative emissions from fossil fuels in the baseline scenario constantly increase. As a consequence, the CN approaches 1, independently of which fossil fuel is substituted (Figure 6, Case A).

If a forest area is clear cut and replaced by a tree plantation, the CN factor follows a significantly different trajectory. The CN factor will rise above zero only when the cumulative emissions from the conversion – including changes in the litter, soil and wood products' pools – are less than the cumulative fossil fuel emissions in the baseline case.

In Figure 6, two further cases are illustrated in which bioenergy plantations replace a forest. In both cases it is assumed that about 50% of the wood extracted from the cleared forest is used for producing bioenergy and the rest for producing harvested wood products (HWPs) additional to the baseline. The aboveground biomass in the cleared forest is equal to 200 t d.m. ha^{-1}. We consider that the forest is replaced by a high productivity plantation of 10 year rotation period (Case B) and a low productivity plantation of 20 year rotation period (Case C). In both cases the new plantation is dedicated to bioenergy production that starts at the end of the first rotation period (10 or 20 years) and continues constantly on an annual basis. The aboveground biomass at the end of the rotation period is about 75 t ha^{-1} when productivity is low and about 160 t ha^{-1} when productivity is high (fast growing species).

In Case B, the initial C loss due to removal of existing forest biomass is repaid before the end of the second rotation period, or 17 years after the forest clear-cut when coal is replaced. After this initial period, the CN increases rapidly to 0.5 at 30 years after conversion and to about 0.9 after 100 years. The pay-back time is a bit longer when oil or gas is replaced, 20 and 25 year respectively. However, when HWPs from the cleared forest are long-lived products, the period in which bioenergy produces more emissions than fossil fuel is shortened because there is initially a smaller reduction in C stocks. In this case, the CN becomes greater than zero from the beginning when coal is substituted for and after an 8-year period if gas is replaced.

When productivity is low (Case C) it can take long periods to repay the initial C loss through fossil fuel substitution, because the amount of wood produced for fuel is relatively small compared to the initial C loss from the ecosystem. In the analyzed case, it takes almost six rotation periods to pay back the carbon lost from the ecosystem when coal is replaced (114 years). The pay-back time increases to 145 and 197 years, respectively, when oil and gas are replaced. In this case, the inclusion of long lived products has no influence on the length of the payback time, because the contribution of the HWP stock to lowering the C stock decrease is not enough to compensate for the initial loss.

Results are strongly influenced by the assumptions made. If a forest with higher C stocks were converted to a plantation, the period needed to compensate for the biomass C loss is longer. The use of the biomass from the cleared forest can also have a strong influence on results. For instance, if the pre-existing forest is cleared with fire rather than harvested and used for a combination of bioenergy and HWPs, the payback times can be much longer. Altering the rotation period of plantations will also influence results. If, for example, the net annual increment is increased by decreasing the rotation period, the compensation period is shorter. Baseline assumptions can also influence the results. For instance, if marginal land in Case A would be afforested in the baseline instead of remaining agricultural land, emissions due to the loss of a potential forest would have to be taken into account.

This analysis can also be applied to indirect land use change to the extent that the indirect land use change connected to a new plantation can be identified. If new plantations are established on agricultural land and crops are displaced onto forest land, the effect is similar to a direct replacement of forest with bioenergy plantations.

4 DISCUSSION AND CONCLUSIONS

The case studies presented in this paper are illustrative examples of different sources of woody biomass for bioenergy. These illustrative examples show that the capability of woody biomass to reduce the anthropogenic emissions in the atmosphere compared to continued use of fossil fuel vary widely depending on the source of biomass that is utilized and time horizon considered.

The paper also points out that the impact of *consumption emissions* varies substantially according to the assumptions made. Some of the key assumptions that influence the development of CN of woody bioenergy over time are: the productivity of stands; the extent to which management practices are changed (e.g. rotation period, change of harvest intensity); the previous land use; and baseline assumptions. In addition, the proportion of felled biomass that is used for bioenergy strongly influences the results. By increasing the amount of biomass that is used for energy, the period in which bioenergy produces more emissions than fossil fuel (CN>0) is shortened.

It should also be kept in mind that a number of other factors contributing to *consumption emissions* were not included in this study. First, the illustrated case studies do not take into account the effect of natural disturbances on the forest C stocks. However, more intensive forest management regimes might reduce the risk of disturbances (Lindner *et al*. 2008; Seidl *et al*. 2008). Aging of forests is a current trend in some European regions and the older the forests, the higher is the risk of disturbances such as pests, windthrows and forest fires. Thus, it remains an open question whether it is a better strategy to store carbon in aging forests, while possibly increasing the risk of abrupt C stock losses, or to use these stocks to produce energy. Forest models that include projections of disturbance risks could help to better identify the trade-offs between C sequestration and bioenergy use and provide a more realistic assessment of the time horizons at which bioenergy would offer benefits over use of fossil fuels.

Second, climate change could affect both forest growth rates and natural disturbance risk and change results. However, climate change would have an influence of forest C stocks both in the bioenergy and the fossil fuel scenario and therefore the difference between the two scenarios might not be so relevant.

Third, as indicated in the Methodology section, the figures reported in this study do not take into account the emissions in the production chain and their effect on the overall mitigation potential of bioenergy. To serve as the basis for decision-making, comprehensive GHG emission profiles which include production chain emissions both in the bioenergy and the fossil fuel systems are needed.

Additional factors have to be taken into account when biomass is diverted from pulp, paper and other forest products to energy. Diversion from other uses might occur because of competition for biomass under increased demand for renewable energy (COM 2008). First, when the biomass is used for energy rather than for harvested wood products (HWPs) such as paper and solidwood products, the saved emissions from replaced fossil fuels have to be compared to the loss of C stock in HWPs. Longer time frames are usually needed to produce the same amount of GHG benefits if wood is diverted from solidwood products to bioenergy, because of their longer life-time compared to paper products. Second, if wood is diverted from other uses, it is likely that these uses will be met either through other materials or by importing biomass from other countries. This raises the question of the emissions caused by use of other materials or by imports for paper, furniture or building. For a true picture of whether it is better to use woody biomass for products or bioenergy, all these emissions need to be assessed.

The strong influence of assumptions made and of the variability of conditions suggests that additional research is needed to allow drawing more realistic conclusions regarding the impact of *consumption emissions* on bioenergy GHG profiles. In particular, more in-depth analysis which includes all representative feedstocks and management regimes within a region or a country, natural disturbances and indirect effects on C stocks in other parts of the world is needed. By accounting for these factors, the impact of *consumption emissions* on the overall GHG profile could be smaller or greater than in the results presented here.

However, in agreement with other recent studies (Cherubini et al. 2011a; McKechnie et al. 2011; Repo et al. 2011; Walker et al. 2010), this study shows that the assumption that bioenergy always results in zero GHG emissions compared to continued use of fossil fuels, i.e., that all biomass is carbon neutral, regardless of the time horizon considered is incorrect. Consequently, the current accounting approach in which no emissions are attributed to combustion of biomass is misleading in the context of the target compliance dates. While it is clear that all sources of woody bioenergy from sustainably managed forests will produce emission reductions in the long term, different bioenergy sources have various impacts in the short-medium term. Therefore, some sources of wood for bioenergy might make no contribution to reducing GHG emissions within the time frame of climate mitigation policies, whereas other sources may have this potential. The study shows that the use of forest residues that are easily decomposable can produce GHG benefits from the beginning of their use and that biomass from dedicated plantations that do not cause significant C stock losses through their establishment can be carbon neutral. On the other hand, the risk of short-to-medium term negative impacts is high when additional fellings are extracted to produce bioenergy and the proportion of felled biomass that is used for bioenergy is low, or when conversion of land to bioenergy plantations results in significant losses of C stocks.

The method used in this study allows tracing a time dependent GHG profile of bioenergy that highlights different impacts over time. Such a method provides an instrument to support the energy sources that are the most beneficial for GHG emission reduction according to time-dependent goals.

It is also shown that the concept of sustainable management does not always correspond to a concept of carbon neutrality. Biomass extracted from forests in which harvest is less than the net annual increment can still result in more GHG emissions than an alternative energy source within near-to-medium time horizons.

This study encourages further research to provide improved and comprehensive assessments of the mitigation potential of different bioenergy sources in comparison with continued use of fossil fuels. It also suggests that current accounting systems are not reflecting the impact that woody bioenergy can have on the atmosphere in the short-medium term.

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Table 1 Equations and parameters used in the forest carbon model

Biomass component (t d.m. ha^{-1})	**Equations**	**Parameters**
Aboveground	$B_{(t)} = B_{(t-1)}\left\{1+\frac{R}{N}\left[1-\left(\frac{B_{(t-1)}}{B_{MAX}}\right)^{N}\right]\right\}$	$R = 0.0205$ $N = -0.5388$ $B_{MAX} = 450$ t ha^{-1}
Roots	Total Root: $R_{(t)} = aB_{(t)}{}^{b}$	$a = 0.064$ $b = 1.257$
	Fine roots: $FR_{(t)} = cR_{(t)}{}^{d}$	$c = 0.452$ $d = 0.632$
Litter	$L_{j\,(t)} = L_{j\,Input} + L_{j\,(t-1)}e^{-1/K_j}$ $L_{j\,Input} = L_{j\,B(In)} + L_{j\,H(In)}$ $L_{j\,H(In)} = \mu \cdot Harv_{(t)}$	Foliage litter, $L_{1(t)}$: $L_{1B(In)}=0.08B_{(t-1)}$; $K_1=5.0$ Woody litter, $L_{2(t)}$: $L_{2B(In)}=0.0177B_{(t-1)}$; $K_2=12.5$ Woody root litter, $L_{3(t)}$: $L_{3B(In)}=0.0177R_{(t-1)}$; $K_3=12.5$ Fine root litter, $L_{4(t)}$: $L_{4B(In)}=0.641FR_{(t-1)}$; $K_4=5.0$ $Harv_{(t)}$:amount of harvested $B_{(t)}$ μ: percentage of $Harv_{(t)}$ left on the forest floor or share of roots affected by harvest (based on root equations)
Soil	$S_{(t)} = S_{(t-1)}e^{-1/K_5} + \varphi_1\sum_{j=1}^{2}\left[1-(L_{j\,(t-1)}e^{-1/K_j})\right] + \varphi_2\sum_{j=3}^{4}\left[1-(L_{j\,(t-1)}e^{-1/K_j})\right]$	$K_5 = 30.0$ $\varphi_1 = 0.05$ $\varphi_2 = 0.50$

Figure 1. C stocks in a forest parcel when a bioenergy system is implemented (dashed line) or in the reference system, when bioenergy is not used to replace fossil fuels (solid line).

Figure 2. Illustration of the CN factor value in relation to GHG benefits. FF: fossil fuels

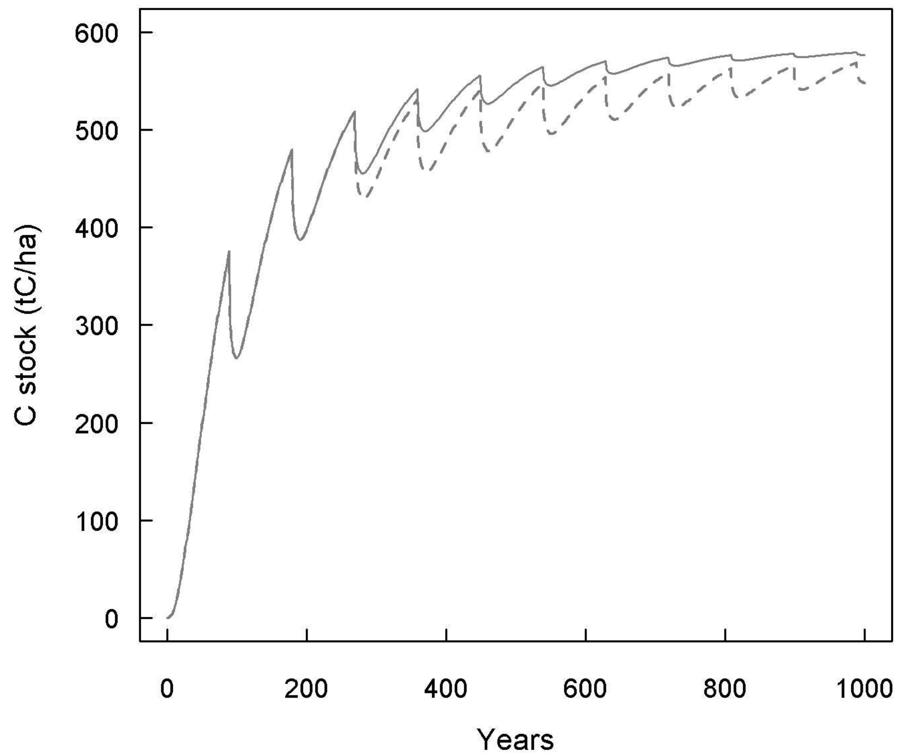
Figure 3. Effect of additional fellings on the C stock in a rotation forest (living biomass, litter and soil). In graph A, fellings are increased from 60% to 80% of the net annual increment which decreases over time. In graph B, the fellings are increased from 60% to 80% of the aboveground biomass in the harvested parcel. The difference between the C stock in the bioenergy scenario (dashed, grey line) and the one in the fossil fuel reference system (solid, grey line) is represented by the C stock change curve (black line, plotted on the secondary y-axis). The point in time when management is changed is indicated by year 0.

Figure 4. *Consumption emissions* due to biomass use from additional fellings (dashed, grey line) compared to *consumption emissions* from use of an equivalent amount of fossil fuel (solid, grey line). The CN factor (black line, plotted on the secondary y-axis) shows when the *consumption emissions* due to change of forest management are higher (CN<0) or lower (CN>0) than the fossil fuel *consumption emissions* in the baseline. In Case 1, the final felling is increased from 60% to 80% of the net annual increment, which decreases over time, while in Case 2 the fellings are increased from 60% to 80%

of the aboveground biomass in the harvested parcel. In each Case, the graphs on the left represent bioenergy substituting coal, while the graphs on the right represent bioenergy substituting natural gas.

Figure 5. C*onsumption emissions* from the use of felling residues for energy (dashed, grey line) compared to *consumption emissions* from use of equivalent amount of fossil fuel (solid, grey, line). The carbon neutrality factor (CN, black line plotted on the secondary y-axis) shows to which extent bioenergy from residues produce GHG emission reductions compared to fossil fuels. The graph on the left represents bioenergy substituting coal, while the graph on the right represents bioenergy substituting natural gas.

Figure 6. Biomass c*onsumption emissions* from a new bioenergy plantation (dashed, grey line) compared to *consumption emissions* from substituted fossil fuel (solid, grey, line). In Case A, the plantation is established on marginal agricultural land and it produces a net C sink, resulting in a CN >1 (black line, plotted on the secondary y-axis). In Case B and C the new bioenergy plantation replaces a forest. Case B illustrates the establishment of a high productivity plantation, while Case C of a low productivity plantation. When the initial C loss is less than the cumulative fossil fuel emissions in the baseline case, CN>0 (black line, secondary y-axis) and bioenergy starts producing emission reductions. In each Case, the graphs on the left represent bioenergy substituting coal, while the graphs on the right represent bioenergy substituting natural gas.



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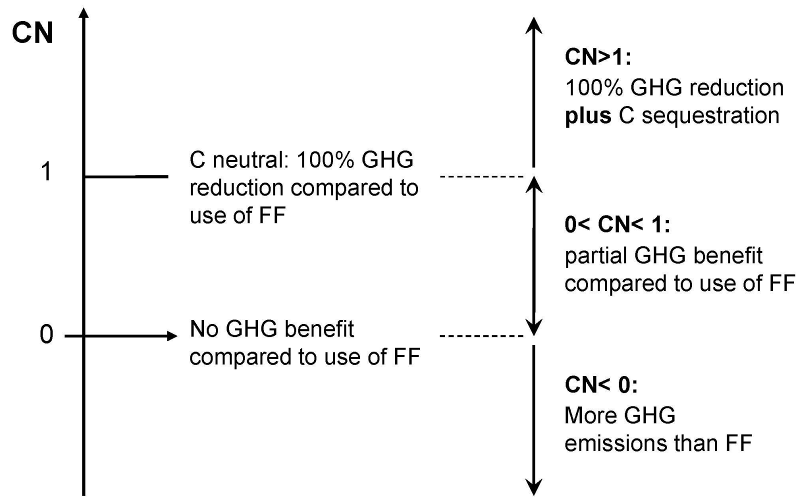

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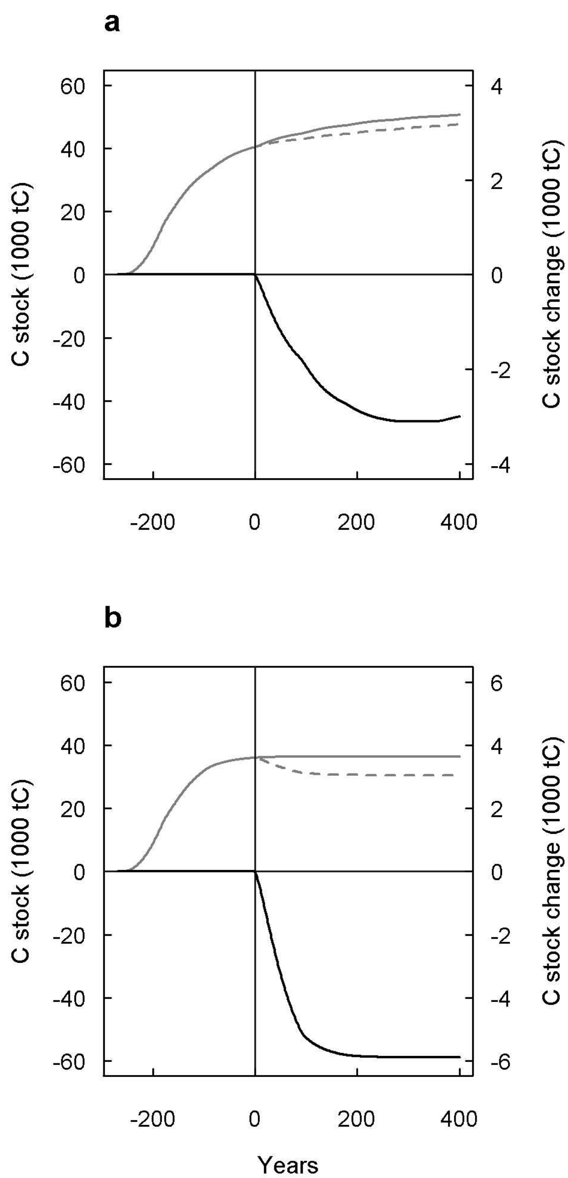

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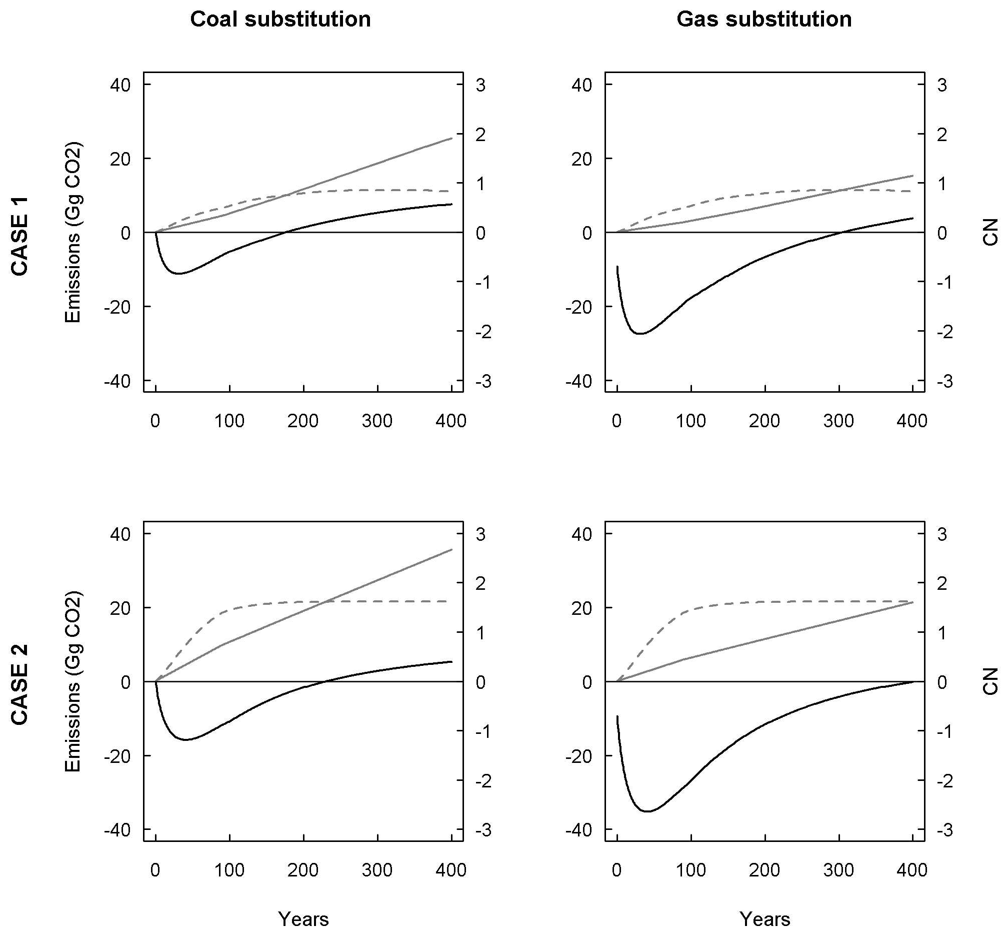

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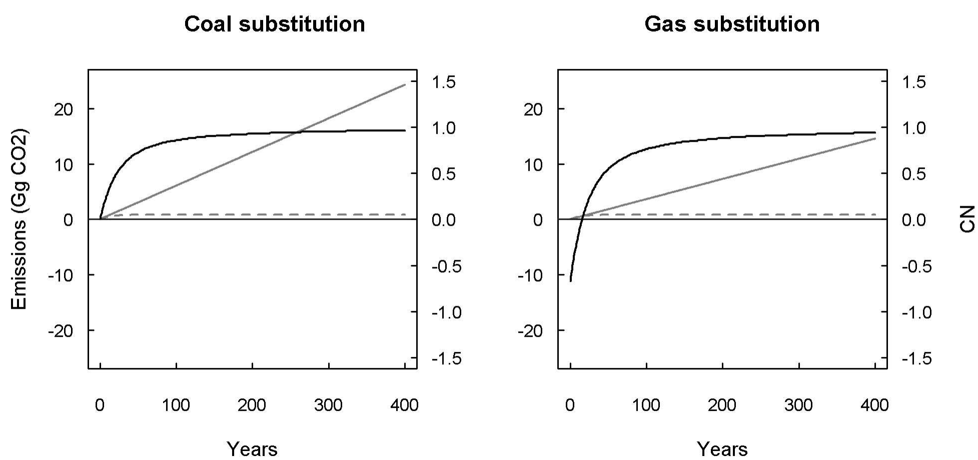

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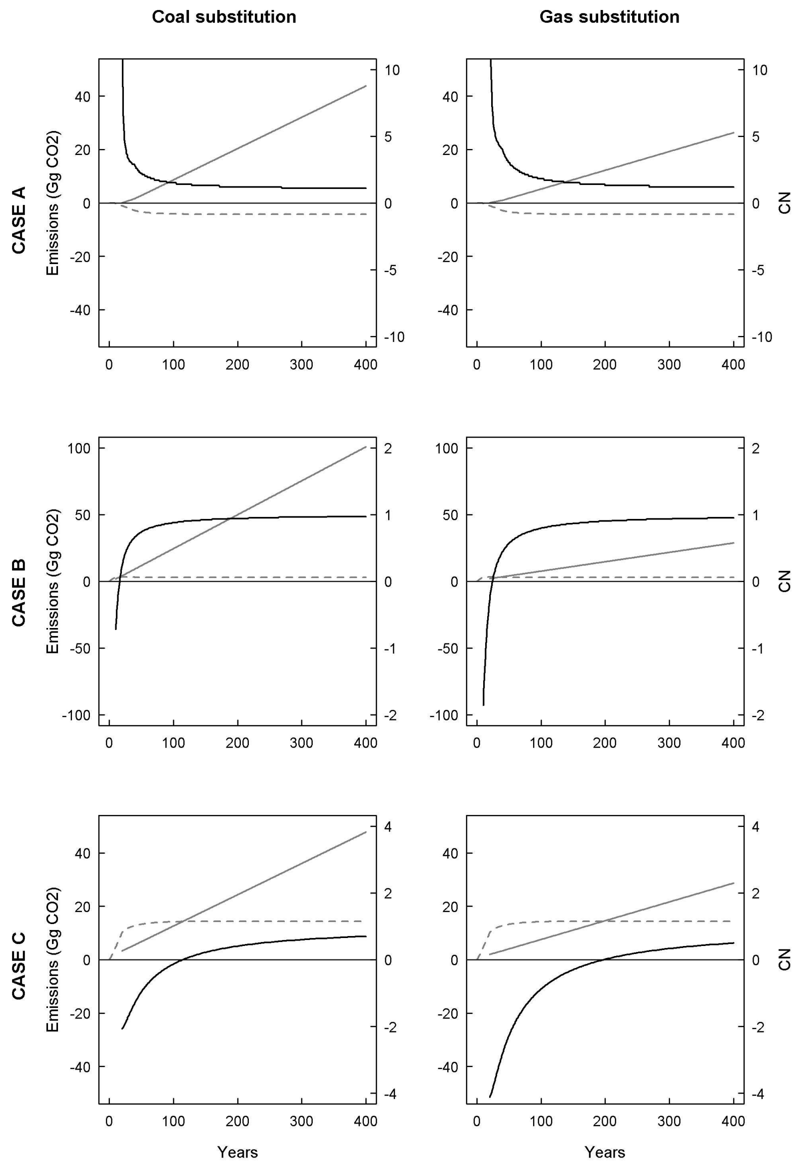

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