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CARBON BALANCE OF BIOENERGY FROM LOGGING RESIDUES

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Abstract—Bioenergy as a substitute for fossil energy is regarded a possibility to reduce the energy related carbon dioxide emissions to the atmosphere, because 'the carbon, which is set free from biomass combustion, is taken up again by regrowing plants and thus the carbon cycle of bioenergy is closed', as it is often argued. In a more detailed analysis of bioenergy strategies, two main effects have to be investigated: on the one hand, carbon in fossil fuels is substituted and thus not emitted to the atmosphere, while on the other hand, the use of biofuels might result in a reduction of carbon stored in the biosphere (plants, litter and soil).

One of the possibilities to use biomass for energy is to burn logging residues from conventional forestry for heat and/or power production. For this type of bioenergy strategy, a model has been developed which allows one to calculate the change in carbon storage in three soil carbon pools and the carbon fluxes to and from these pools. The model results indicate that the carbon stored in the forest soil is reduced when logging residues are removed for bioenergy to displace fossil fuels. However, this effect is limited, as eventually a new equilibrium of carbon storage in the forest soil is reached, while fossil fuel substitution is continued further on. The time-dependent characteristic value 'carbon neutrality' (*CN*), which is the ratio of net emission reduction (fossil fuel substitution minus carbon losses of the soil) to the 'saved' carbon emissions from the substituted reference energy system, reflects this effect. *CN* equal to one means that bioenergy is completely 'CO_2-neutral'. For bioenergy from logging residues, *CN* is very low at the beginning when bioenergy is introduced, increases continuously and approaches one at infinity. According to the results of parameter studies, *CN* of bioenergy from logging residues in temperate and boreal forests lies between 0.49 and 0.82 after 20 years and between 0.75 and 0.88 after 100 years.

Keywords—Logging residues; forestry; soil; carbon balance; carbon cycle; carbon dioxide; biomass; energy; bioenergy.

1. INTRODUCTION

Bioenergy is regarded as one possible substitute for fossil fuels, which contribute substantially to the rise of carbon dioxide in the atmosphere and thus cause long-term changes of the global carbon cycle. On the other hand, biomass itself is part of the global carbon cycle, taking up carbon from the atmosphere, storing it temporarily and releasing it partly back to the atmosphere and partly to the soil. Thus, both the reduction of carbon emissions from fossil fuels and the influence of biomass removal on carbon pool sizes and carbon fluxes have to be analysed to estimate the net reduction of carbon emissions through the use of bioenergy.

It is generally assumed that biomass as an energy carrier is 'CO_2-neutral'. This means that there are no net carbon emissions when, for instance, wood chips are burned in a furnace. This assumption is based on the reasoning that the carbon stored in plants, which is emitted through combustion in a furnace, is taken up again by the regrowing plants. On the other hand, it is sometimes argued that bioenergy is not 'CO_2-neutral' for the following reasons:

1. Combustion of biomass fuels and regrowth of plants do not take place at the same time.[1] Depending on the time scale taken into account, this effect is of greater or lesser importance.
2. Soil carbon pool sizes might decrease when a part of the plant litter is used for bioenergy and thus the input of plant litter to the soil is reduced.[2]
3. Bioenergy strategies might interfere with 'natural' carbon storage, since with some of these strategies the amount of carbon stored in the biosphere may decrease or may be prevented from increasing.[3,4,5]
4. The amount of carbon emitted per unit of

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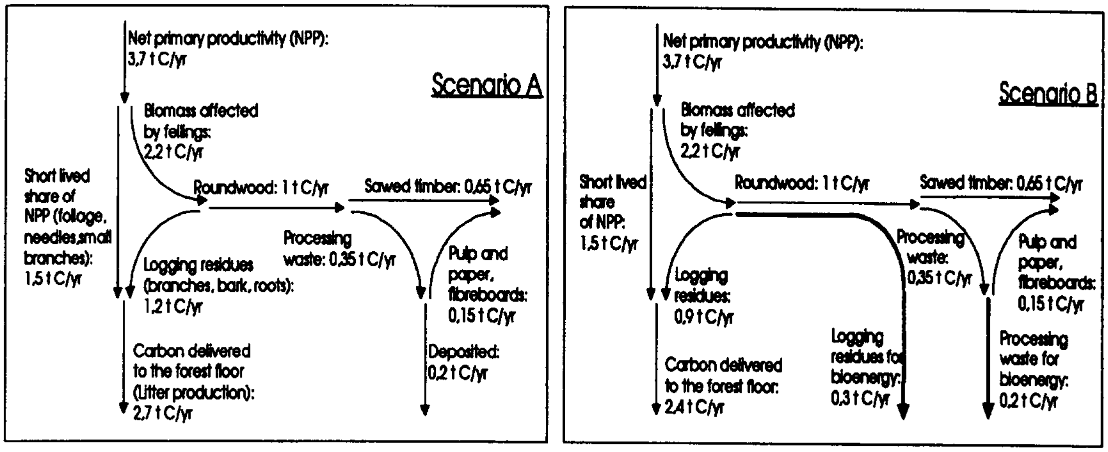

Fig. 1. Carbon fluxes per hectare in forestry and wood industry without (Scenario A) and with (Scenario B) use of logging residues and processing waste for bioenergy.

produced energy (carbon emission rate) is higher for biomass fuels than for the average mix of fossil fuels.

5. The efficiency of bioenergy systems is in many cases not yet as high as that of fossil fuel systems.
6. Many bioenergy systems require some fossil fuel input for system operation or maintenance.

Arguments 1–3 concern the biospheric carbon balance, while arguments 4–6 concern the carbon balance of energy conversion. In order to take all the arguments into account, a complete carbon balance of bioenergy systems is necessary. For every bioenergy strategy under consideration the carbon gain (fossil carbon that is no longer emitted) and the carbon losses (net emissions of carbon from the biosphere) have to be calculated and balanced. In this study the **biospheric** carbon balance of bioenergy from logging residues and wood processing waste are of interest. Other sources of bioenergy and the carbon balance of energy conversion are treated separately.[6,7]

2. BIOENERGY FROM LOGGING RESIDUES AND WOOD PROCESSING WASTE

A very common bioenergy strategy is to burn residues from conventional forestry and wood processing waste in biomass furnaces to produce heat and/or power. The two most important methods of conventional forestry are:

- Selective harvesting, where only some trees of a forest are cut.
- Clear cutting and regrowing larger portions of a forest.

In this study, the results of computer model analyses for the carbon balance of bioenergy will be shown in detail for selective harvesting (Section 4). For clear cutting, which has been analysed similarly, the most important results will be shown (Section 5).

A basic assumption of this analysis of bioenergy from logging residues is an equilibrium of carbon pool sizes in present forestry and wood industry as an initial condition. Presently residues like branches or bark often remain in the forest and are added to the litter layer, after the trees have been cut and the roundwood has been taken out. Additional removal of parts of these residues for bioenergy has no direct effect* on the carbon storage in trees, but will cause a decreased flux of carbon into the forest litter and soil resulting in a reduction of the carbon storage in these pools.

Tropical forests have very different characteristics compared to temperate and boreal forests, as far as the behaviour of forest soils is concerned. The calculations in this study are restricted to the temperate and boreal forests.

The UN-ECE/FAO study[8] states that in 1990, in temperate and boreal forests, 1.86 billion m^3 of roundwood (overbark) were felled, which is said to be "probably an underestimation". 93% of these fellings took place in exploitable forests for which data on the net annual increment (NAI) are given also. The NAI in exploitable forests has been reported to be larger than the net annual fellings by approximately 0.560 billion m^3. Thus, these forests become a net sink of CO_2 amounting approximately to 300 Mt C yr^{-1} (using the

*An indirect effect might be caused by a reduced supply of nutrients.

conversion factor 0.54 tC m^{-3} stored in roundwood plus branches and roots relative to the roundwood volume.[9]

Figure 1 shows the flux of carbon in a forestry scenario without energy production (Scenario A) and in a forestry scenario where parts of the residues and the wood processing waste are used for energy production (Scenario B). The numbers demonstrated in the figure correspond to a typical European forest (see for example Burschel *et al.*[10]) and refer to an area of one hectare. It is assumed that from European forests under exploitation an average of 4.4 m^3 ha^{-1} of roundwood could be removed potentially. In fact it is less by 10–30% because the NAI exceeds the harvest at present time.[11] For our model presentation we have chosen an annual harvest of 3.7 m^3 roundwood corresponding to 1 tC.[12]

2.1. *Scenario A*

According to Mitscherlich and Moll[13] about 40% of net primary productivity (NPP) are for leaves, feeder roots and fruits, 10% are for branches, 15% for roots and 35% for stemwood. We assume here that, in order to produce the above mentioned 1 tC ha^{-1} yr^{-1} of roundwood, about 3.7 tC ha^{-1} yr^{-1} of NPP are necessary. The short-lived share of this NPP (foliage, needles, small branches) is about 1.5 tC ha^{-1} yr^{-1} (40%). From the remaining flux, 1 tC ha^{-1} yr^{-1} are currently taken away as roundwood (27% of NPP, which is lower than the 35% for stemwood in Mitscherlich and Moll, because the assumption is that not all stemwood is used) and 1.2 tC ha^{-1} yr^{-1} remain as broken stems, branches, tops, bark and roots in the forest (logging residues). In Austria, 35% of harvested roundwood going through sawmills is processing waste (sawdust and other woody residues[14]). Bernow *et al.*[15] also estimate 35% for the Southern New England region. Taking the assumed 1 tC ha^{-1} yr^{-1} of roundwood, 0.65 tC ha^{-1} yr^{-1} remain as sawed timber and of the remaining 0.35 tC ha^{-1} yr^{-1} of processing waste about 0.15 tC yr^{-1} are used in pulp and paper industry and for fibreboard production, 0.2 tC ha^{-1} yr^{-1} is deposited in landfills and left to decay. According to Bernow *et al.*, about 50% of wood processing residues decay and produce greenhouse gases.

2.2. *Scenario B*

In a modification of Scenario A, 0.3 tC ha^{-1} yr^{-1} of logging residues and 0.2 tC ha^{-1} yr^{-1} currently deposited processing waste are used for bioenergy. We use the analysis of Bernow *et al.* to estimate these values. If the total biomass affected by harvesting (2.2 tC ha^{-1} yr^{-1}) includes 1.54 tC ha^{-1} yr^{-1} above ground and 0.66 tC ha^{-1} yr^{-1} below ground and 70% of the above ground biomass is removed as roundwood for milling, the total removed as roundwood would be 1.08 tC ha^{-1} yr^{-1} with 0.46 tC ha^{-1} yr^{-1} as above ground logging residues. If 2/3 of above ground residues can be recovered for bioenergy, we derive the 0.3 tC ha^{-1} yr^{-1} shown in Scenario B as recoverable bioenergy for each approximately 1 tC ha^{-1} yr^{-1} harvested as roundwood.

The numbers in Scenario B concerning bioenergy indicate that the total carbon used for bioenergy is about 50% of the carbon in roundwood removed from forests. Roundwood production (1990) amounted to 1.55 billion m^3 in the developed countries,[16] corresponding approximately to the harvest in temperate and boreal forests. Using the conversion factor of 0.27 tC m^{-3} to calculate the carbon content of the roundwood, this gives a total potential of about 0.21 GtC yr^{-1} available for bioenergy, which is around 3.5% of the current emissions from global fossil energy consumption of 6 GtC yr^{-1}.

Both Scenario A and Scenario B represent extreme cases. In some countries, the forestry and wood industries might be closer to one and in some countries closer to the other case. In this study the transition from the one extreme case into the other is described.

It must be mentioned that the introduction of forestry as shown in Scenario A also causes a change of carbon pools and fluxes, because without any human activity even more carbon would reach the forest soil. This impact of conventional forestry is even stronger than that of additional removal of logging residues. However, conventional forestry has been practiced for hundreds of years and thus it is assumed that the carbon pools and fluxes in these forests have reached a new equilibrium in Scenario A. Compared to this development, the additional removal of logging residues might be introduced in a short timespan if bioenergy strategies are considered an effective measure against the increase of the atmospheric CO_2 concentration. Therefore the impact of energy production from logging residues on carbon stored in forest soils has to be studied in detail.

As shown in Fig. 1, there are two sources of bioenergy for the situation in Scenario B:

1. Parts of the logging residues (mainly branches, broken stems and bark), that have previously been left in the forest and are now used for bioenergy.
2. Processing waste from wood industry (sawmills, wood product manufacturing), that has previously been discarded and is now used for bioenergy.

Source (1) has been examined by detailed calculations. Source (2) has similar characteristics concerning the carbon balance to source (1) under the assumption that the decomposition rate of wood residues in landfills is the same as in forest soils. Given the assumption that decomposition rates in landfills are lower than in forest soils, then source (2) would have a worse carbon balance (less net carbon gain by substituting fossil fuels through bioenergy from this source) compared to source (1), and vice versa. Further on bioenergy production from source (1) is investigated in detail.

3. DEFINITIONS AND METHODS

To analyze the effects of displacing fossil fuels by biofuels from logging residues and processing waste, the parameter 'Carbon Neutrality' is introduced and the method of calculating it is derived.

3.1. *Carbon neutrality*: *CN*

If a measure introducing biomass as a substitute for a certain fossil energy carrier is considered, the question is: to what extent does this measure actually reduce carbon emissions? 'Carbon Neutrality' (*CN*) is defined here as the ratio of the net reduction of carbon emissions to the 'saved' carbon emissions from the substituted reference energy system, over a certain period of time and provides a useful, time-dependent measure of the extent to which an alternate energy system yields a net reduction in CO_2 emissions.

$$CN(t) = [C_{\mathrm{ref}}(t) - C_{\mathrm{new}}(t)]/C_{\mathrm{ref}}(t) = 1 - C_{\mathrm{new}}(t)/C_{\mathrm{ref}}(t), \quad (1)$$

where $C_{\mathrm{ref}}(t)$ = carbon emissions of the fossil reference energy system in the timespan between 0 and t years [kg C]. This reference system would have been established or would have continued to operate in a 'reference' case without bioenergy use. $C_{\mathrm{new}}(t)$ = net carbon emissions of the new bioenergy system in the timespan between 0 and t years, i.e. the net biospheric carbon emissions and the carbon emissions from auxiliary fossil fuels [kg C]. t = Time since the introduction of the bioenergy system [years].

In other words *CN* may be expressed as:

$$CN\,(t) = (\text{saved carbon} - \text{emitted carbon})/\text{saved carbon}. \quad (2)$$

In an ideal case the bioenergy system causes no net carbon emissions at all and is 'CO_2 neutral', i.e. *CN* is 1. *CN* is 0 if the bioenergy system causes the same amount of net carbon emissions as the substituted fossil energy system did.

As mentioned in the Introduction, emphasis in this study is on the biospheric carbon balance. Thus it is assumed, that

- the fossil energy system and the bioenergy system have the same efficiency of conversion;
- auxiliary fossil energy consumption for biomass fuel production can be neglected; and
- the substituted fossil fuel has the same carbon emission rate as biomass which, in an approximation, means that coal is substituted.

In this case $CN(t)$ is a function of the biospheric carbon balance only and the terms used in Equation 1 become:

$$C_{\mathrm{ref}}(t) = C_{\mathrm{Bio}}(t) \quad C_{\mathrm{new}}(t) = C_{\mathrm{Loss}}(t),$$

where $C_{\mathrm{Bio}}(t)$ = amount of carbon embodied in logging residues that are used for bioenergy in the timespan between 0 and t years [kg C]. $C_{\mathrm{Loss}}(t)$ = net amount of carbon that has been set free from biomass, litter and soil in the timespan between 0 and t years [kg C]. Another form to express $C_{\mathrm{Loss}}(t)$ is $C_{\mathrm{Loss}}(t) = \mathrm{Carbon}(0) - \mathrm{Carbon}(t)$, where $\mathrm{Carbon}(t)$ is the amount of carbon stored in vegetation, litter and soil at time t. Equation 1 becomes

$$CN(t) = [C_{\mathrm{Bio}}(t) - C_{\mathrm{Loss}}(t)]/C_{\mathrm{Bio}}(t) = 1 - C_{\mathrm{Loss}}(t)/C_{\mathrm{Bio}}(t). \quad (3)$$

$CN(t)$ is time dependent, because the amount of biomass removed and of biospheric carbon losses are accumulating with time. The term $1 - CN(t)$ represents the ratio of biospheric carbon losses to the amount of carbon removed for bioenergy. $CN(t)$ is 1 if there are no losses of carbon from the biosphere (vegetation, litter and soil) at time t. $CN(t)$ will be 0 if $C_{\mathrm{Loss}}(t)$ equals $C_{\mathrm{Bio}}(t)$, which means that the removed and burned carbon is not replaced in the biosphere at all. In this study we

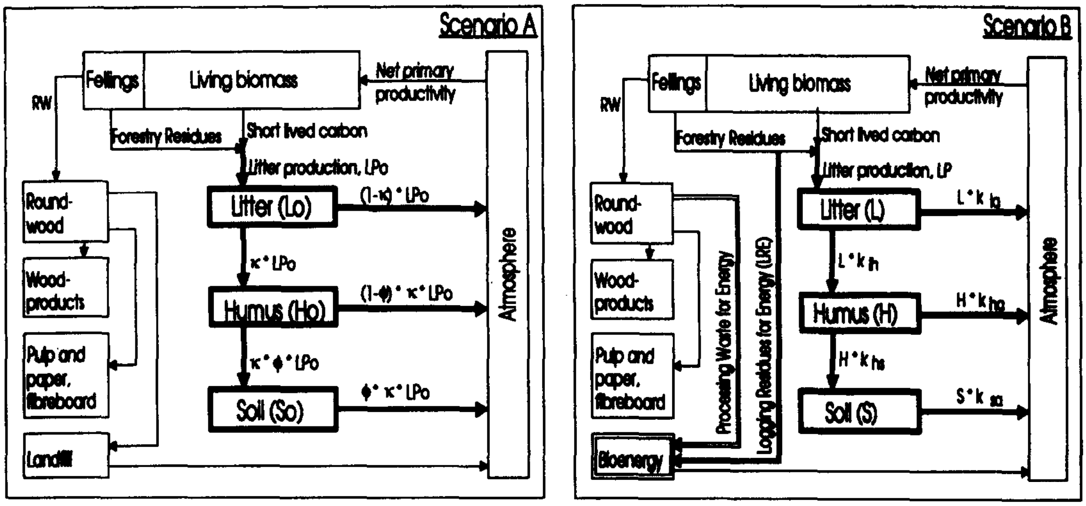

Fig. 2. Global carbon pools and fluxes in forestry and wood industry as described by the computer model (thick lines), without (Scenario A) and with (Scenario B) use of logging residues and processing waste for bioenergy. See Appendix for further explanation.

assume that an equilibrium has been achieved in managing the above-ground harvestable biomass and that this equilibrium will not be disturbed by diverting residues to bioenergy production. We did not include effects like availability of nutrients or other secondary effects that influence forest growth or maximum standing stock.

For the evaluation of bioenergy strategies from a carbon balance point of view, not only CN is of interest, but also the net emission reduction, for example per unit area. This net emission reduction can be calculated as $C_{\mathrm{Bio}} - C_{\mathrm{Loss}}$ or as $CN \times C_{\mathrm{Bio}}$.

3.2. *The model*

The concept of the model describing carbon pools and fluxes follows the 'Frankfurt Biosphere Model' (FBM, Kohlmaier *et al.*[17]) which is used for calculating the long-term development of biomass and soil on a global scale. The decay of organic material is generally described (Van Breemen *et al.*[18]) by the equation

$$\mathrm{d}C/\mathrm{d}t = -kC, \tag{4}$$

which can be solved as

$$C(t)/C(0) = \mathrm{e}^{-kt}, \tag{5}$$

where $C(0)$ = amount of organic carbon at time 0, $C(t)$ = amount of organic carbon at time t, and k = decomposition constant.

We have used this equation to calculate carbon fluxes, carbon pool sizes and CN with additional removal of logging residues for bioenergy uses. The soil and litter carbon has been divided into three carbon pools:

- litter pool (containing dead organic matter like leaves, needles or branches) with a mean carbon residence time of a few years;
- humus pool, which receives carbon input from the litter pool and delivers carbon to the soil pool, with a mean carbon residence time of up to one hundred years; and
- soil pool with a mean carbon residence time of several hundred years.

For the initial conditions, an equilibrium of carbon pools and fluxes is assumed (Fig. 2, Scenario A). The removal of logging residues causes some deviations from this equilibrium (Fig. 2, Scenario B). As mentioned in Section 2, wood processing waste is not included in the detailed analysis. However, the phenomena of interest (depletion of wood processing waste in landfills and depletion of logging residues in forests) are expected to be similar at least in a first order of magnitude.

A detailed description of the parameters and the model calculations is in Appendix A.

4. RESULTS: LOGGING RESIDUES FROM SELECTIVE HARVESTING

All model calculations have been made for one hectare of forest and thus all values refer to one hectare. Typical values for pool sizes and fluxes reflect the European forest situation where for instance data can be found in Burschel *et al.*[10] Parameter assumptions (parameter definitions are given in Appendix A) for a base case describing the transition from Scenario A to Scenario B are:

$L_o = 13$ tC ha^{-1},
$H_o = 80$ tC ha^{-1},
$S_o = 27$ tC ha^{-1},
$NPP = 3.7$ tC ha^{-1} yr^{-1},
$RW = 1.0$ tC ha^{-1} yr^{-1}
$LP_o = NPP - RW = 2.7$ tC ha^{-1} yr^{-1}
$LRE = 0.3$ tC ha^{-1} yr^{-1},
$\kappa = 0.25$,
$\phi = 0.1$.

The parameters κ and ϕ have been adjusted to represent the expected range of carbon turnover times in the soil.

After the base case calculations (Section 4.1), a number of parameter variations has been made to show the sensitivity of the model (Section 4.2). Additional calculations have been performed for special cases (Section 4.3):

- Should energy production from logging residues be continued?
- Substitution for oil instead of coal.

4.1. *Base case results*

Figure 3 shows carbon pool sizes over time when removal of logging residues and the corresponding lower litter production start at time 0. Obviously the size of the litter pool L decreases first. This is due to the facts that the flux into the litter pool is immediately reduced and that the litter pool has the shortest mean carbon residence time. The mean residence time or lifetime is the ratio of pool size to input flux of carbon. The litter pool is comparatively small and has a high input flux of carbon, which results in a very short mean carbon residence time (about 1–5 years). Humus pool H and soil pool S have longer residence times and therefore need more time to react to the reduced litter production. In Fig. 4 the losses of soil carbon (C_{Loss}) and the carbon in removed and burned biomass (C_{Bio}) (which is equal to the substituted fossil carbon, C_{ref}) are shown, both cumulative over time. Removed carbon increases linearly, whereas losses of soil carbon approach a limiting value. Thus the relative magnitude of the losses compared to the removed logging residues decreases with time. In Fig. 5, removed biomass and biospheric losses are shown on a yearly basis. Again it becomes apparent that losses are small compared to removed biomass in the long run.

Figure 6 displays CN according to Equation A21, see Appendix A. CN is 0 at the beginning and approaches 1 asymptotically in the long run; CN equal to 0 can be explained as follows: if for example a branch containing 100 kg C is burned, the litter pool size is reduced by 100 kg C. Therefore C_{Bio} equals C_{Loss} and CN must be 0. If this is repeated for 50 years, CN is about 0.7, which can be interpreted as follows: each year 100 kg C have been taken out of the forest. This gives a total of 5 tC in 50 years. In the same period the carbon pools have a net loss of 1.5 tC, because the amount of carbon, that would have been delivered to the soil pools in a reference case without wood removal, is reduced, whereas the

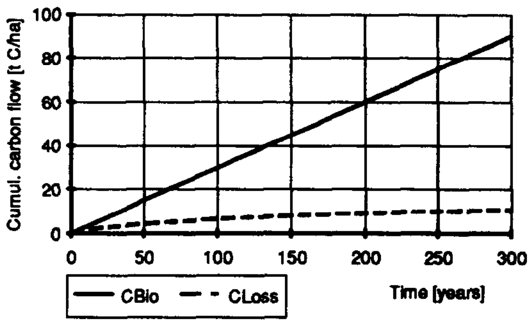

Fig. 4. Cumulative carbon in removed biomass (C_{Bio}) and biospheric carbon loss (C_{Loss}) as a function of time.

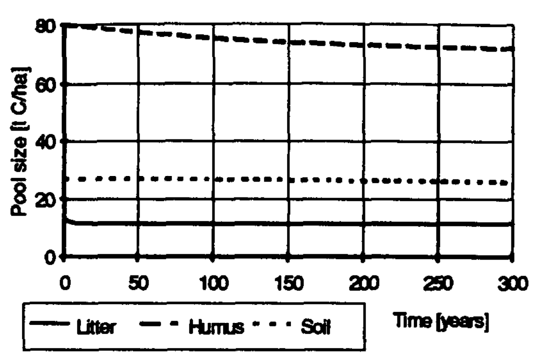

Fig. 3. Sizes of litter, humus and soil carbon pools as a function of time.

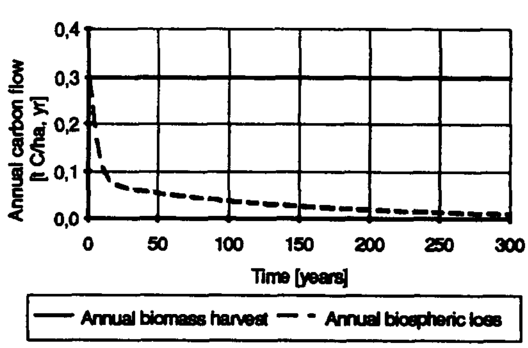

Fig. 5. Carbon in removed biomass, biospheric carbon loss (annually).

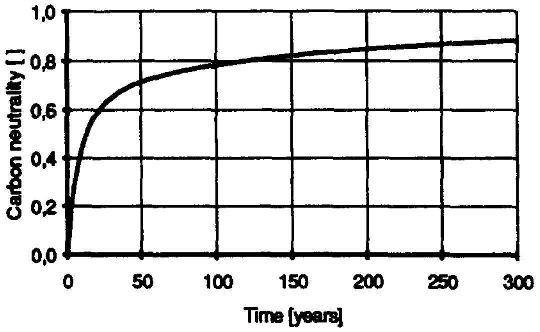

Fig. 6. *CN* for burning logging residues for energy production.

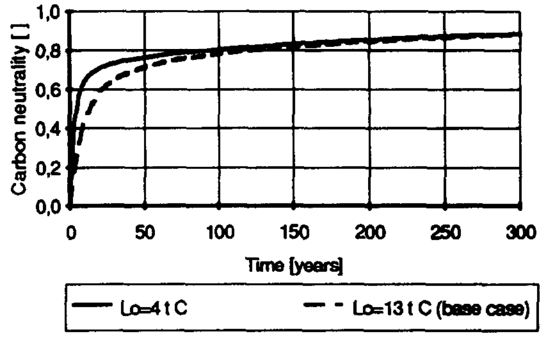

Fig. 8. *CN* calculated for different initial litter pool sizes.

carbon emissions from the pools to the atmosphere are not reduced at the same rate. The ratio of C_{Bio} (5 t) minus C_{Loss} (1.5 t) to C_{Bio} gives a *CN* of 0.7.

The balance in Fig. 6 is an overall balance from 0 to *t*. On the other hand, annual balances are of interest, too. In Fig. 7 the so called 'Annual Carbon Neutrality' (*ACN*) or 'marginal carbon neutrality' is represented. *ACN* also starts at 0 for time 0, but subsequent values are higher than for *CN*. The reason for this is that *CN*, derived from cumulative carbon flows, accounts for the initially high ratio of C_{Loss}/C_{Bio}, whereas *ACN* as an annual value does not contain this 'initial handicap'.

4.2. *Parameter variations*

The sensitivity of the model and of the major results regarding parameter variations is investigated. In each of the following subchapters the result for *CN* in the base case (Fig. 6) is compared to the result with modified parameters.

4.2.1. *Litter pool.* In Fig. 8, *CN* has been calculated assuming a smaller initial litter pool L_o while the humus pool was expanded so that the total carbon is the same. The original litter pool size of 13 tC ha^{-1} corresponds to a mean residence time of 4.8 years, the new pool size of 4 tC ha^{-1} to about 1.5 years.

CN is higher than in the base case, especially in the first 100 years. An explanation is that the litter pool, which is the first carbon pool to be reduced, comes into the new equilibrium faster than in the base case, and that the losses due to the decrease of carbon in the litter pool are smaller. In the longer run this effect can be neglected as the two curves approach each other.

4.2.2. *Partitioning factor* κ. κ is the share of the carbon flux out of the litter pool that enters the humus pool. $(1 - \kappa)$ is emitted to the atmosphere. κ is 0.25 in the base case, which means that 25% of the carbon flux out of the litter pool are delivered to the humus pool and 75% are directly emitted to the atmosphere. *CN* was in addition calculated for $\kappa = 0.4$, 0.12 and, as an extreme case, for $\kappa = 0$ (Fig. 9). For $\kappa = 0$, the humus and soil layers are not involved in the carbon balance. Carbon losses result only from the litter pool and thus are relatively small. $\kappa = 0.4$ corresponds to a mean residence time of carbon in the humus pool of about 75 years (for lower κ the mean residence time is higher).

Obviously a smaller κ results in a higher *CN*, especially after several years. The amount of C in

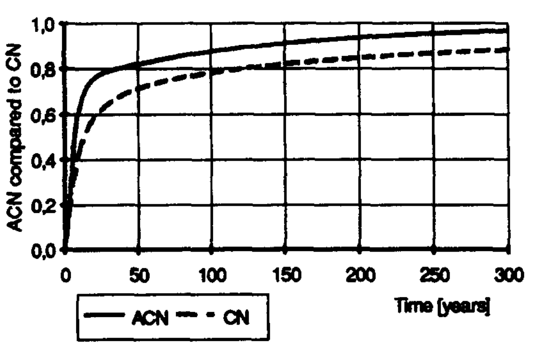

Fig. 7. Annual carbon neutrality (*ACN*), and carbon neutrality for time 0 to *t* (*CN*).

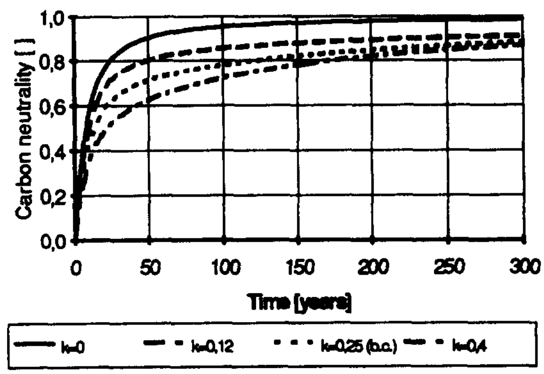

Fig. 9. *CN* calculated for different partitioning factors κ (b.c. = base case).

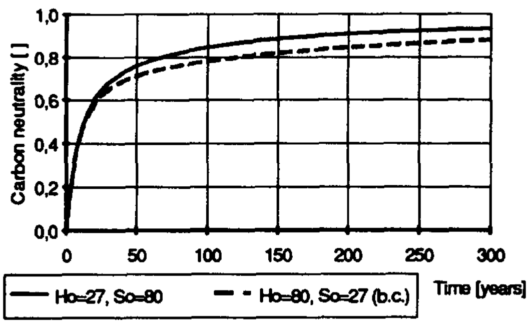

Fig. 10. *CN*, humus and soil pool exchanged in size (b.c. = base case).

the litter pool does not depend on κ, because only the partitioning and not the magnitude of the output flux from the litter pool is influenced by κ. In the first few years the major carbon losses come from the litter pool and therefore determine *CN*, which hence is almost the same in all three cases at the beginning. With a smaller κ, the humus and the soil pool have a smaller input flux and therefore a higher mean residence time. Consequently, the losses in these pools are delayed compared to the base case and—with the same amount of substituted fossil carbon as in the base case—*CN* must be higher for smaller κ values in the long run.

4.2.3. *Humus and soil pools*. The soil and litter carbon in this model is divided into three pools with different mean residence times: litter, humus and soil pools. Thus, it is necessary to test the sensitivity of the model results regarding the relative size of these pools compared to the total amount of soil and litter carbon. In Fig. 10, results are drawn for this variation. The litter pool was kept the same, because it is well accepted that this pool is the smallest one.

In the short run, *CN* remains the same, as the litter pool reacting first on biomass removal has not been changed. The humus pool has been reduced, whereas the soil pool, which reacts after very long time, has been enlarged compared to the base case. As a result the carbon losses in a medium timescale (50–250 years) are lower and therefore *CN* is higher. The carbon losses are delayed into the very far future and the two curves come closer again after 300 years and more.

4.2.4. *Number of pools*. The basic model calculations described in this study used three carbon pools (litter, humus and soil layer). In order to evaluate the influence of the number of pools, calculations were performed with one and two pools, respectively, where the total carbon at the beginning was the same. Results can be seen in Fig. 11.

The behaviour of a one pool model—which does not correspond to reality and was only included as a theoretical extreme case—is strongly different from the two or three pool models. In the base case (three pools) the litter pool delivers 75% of its carbon output flux to the atmosphere and 25% are delivered to the humus pool. Thus, the litter pool serves as a 'filter'. A reduction of litter production does not affect the input flux to the humus pool as much as if 100% of the litter production went into the humus pool, as in the one pool model under discussion. The two and three pool models show similar results. In the first few years there are no differences at all, because the litter pool drives the carbon losses at the beginning. In the long run, some slight deviations can be detected, but as cumulative fossil fuel substitution is already very high until then, this effect is not of importance.

4.2.5. *Pool sizes from Turner* et al. Turner *et al.*[19] subdivide the carbon stored in U.S. timberland into living trees (31%), forest floor (6%), woody debris (11%), understory (1%) and soil (51%). If living trees and understory are not taken into account, then the remaining pools are forest floor (9%, fast decay), woody debris (16%, intermediate decay) and soil (75%, slow decay). The litter pool here corresponds to the forest floor and woody debris pools in Turner *et al.*[19], and the soil pool here corresponds to the soil pool in Turner *et al.*[19] Thus we assumed that 25% of the carbon is in the litter pool and 75% in the soil pool (parameters are: $L_o = 30$ tC ha^{-1}, $S_o = 90$ tC ha^{-1}, $\kappa = 0.25$) and the corresponding mean residence times are 11 and 133 years. Results for this scenario can be seen in Fig. 12. As already shown in Section 4.2.1, the larger initial litter pool results in a lower *CN*.

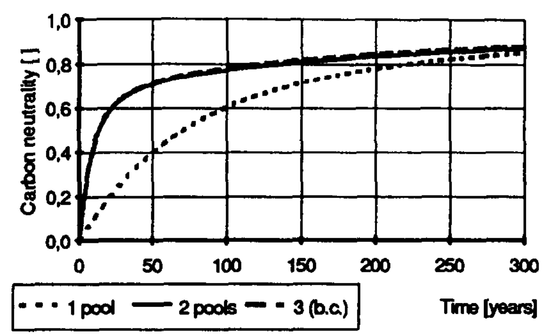

Fig. 11. *CN* calculated for different numbers of pools (b.c. = base case).

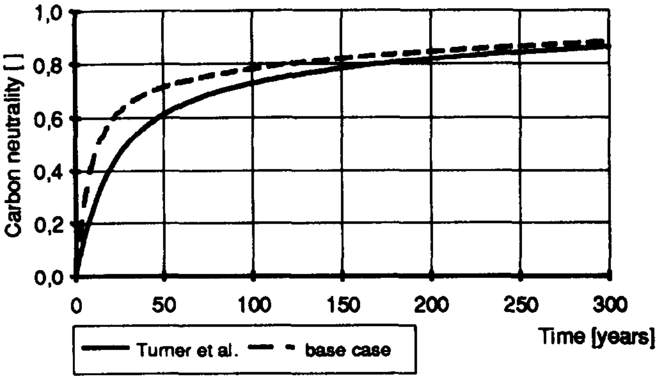

Fig. 12. CN calculated for a set of parameters derived from Turner *et al.*[19] and for the base case.

4.2.6. *Linear increase of residue removal.* In the base-case assumptions, the combustion of logging residues is introduced at time 0 and remains constant thereafter. In reality, an increase of the size of the bioenergy system is more likely to take place. Therefore, it was assumed that the whole system grows linearly for 50 years until the total potential of logging residues is exploited. In this case it is necessary to include 50 ha of forest in the model, so that in each year another hectare can be utilized for bioenergy additionally. However, for comparison reasons the results are given as average numbers per hectare. The carbon balance still includes all emissions and soil carbon losses from time 0 to t. In Fig. 13, the cumulative values C_{Bio} and C_{Loss} are drawn. This figure can be compared to Fig. 4, where C_{Bio} and C_{Loss} are shown for a sudden introduction of bioenergy at time 0. C_{Bio} is a parabolic function between time 0 and 50 years; beyond 50 years, C_{Bio} is linear. Figure 14 represents the CN curves for phase-in periods of 50 and 20 years and for the base case.

CN is lower than in the base case at the beginning. The highest deviations occur after about 50 years and 20 years, respectively. After about 200 years there is almost no difference, because the three cases are equal in the long run—except for their 'history' between 0 and 20/50 years.

4.2.7. *Expected range for CN.* Results for CN from the previous sections are compiled in Fig. 15 and cover a field that is expected to describe reality. In one of the parameter sets, κ and L_o were modified simultaneously.

4.3. *Special cases*

4.3.1. *Should energy production from logging residues be continued?* For a situation where the logging residues have been used for bioenergy in the past, stopping the removal of logging residues would result in an increase of carbon pool sizes, as the losses of the past would be regained again. For an example where after 50 years it is to be decided whether to continue or to stop energy production from logging residues, carbon pool sizes are shown in Fig. 16 for both cases. Continued harvest of logging residues would result in 'saved' fossil carbon emissions (C_{Bio}, as in all previous cases) compared to stopping bioenergy use. However, a continued harvest also results in a 'lost opportunity' to store carbon. This lost opportunity is the gap between the carbon pool sizes in the two cases in Fig. 16.

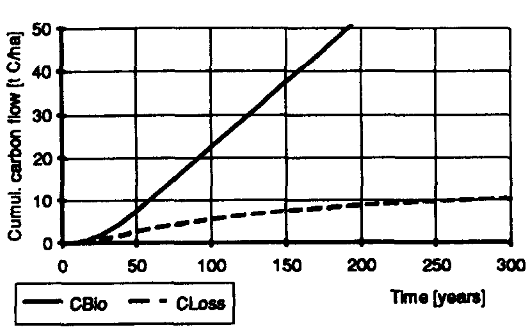

Fig. 13. C_{Bio}, C_{Loss} for the growing system, introduction of bioenergy takes 50 years.

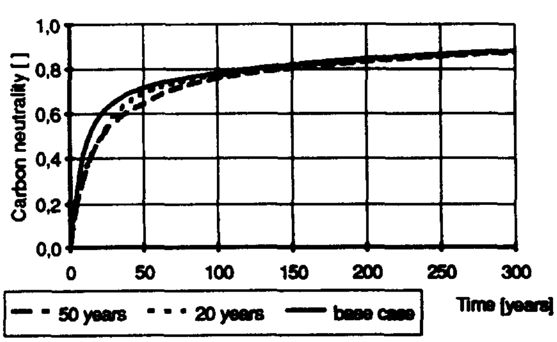

Fig. 14. CN for the growing system, introduction of bioenergy takes 20/50 years.

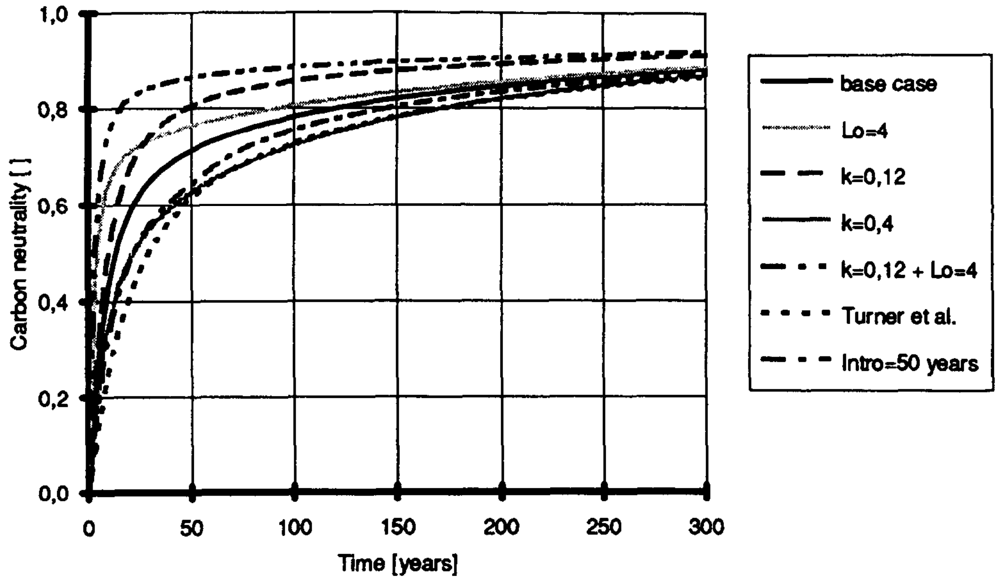

Fig. 15. Results of parameter variations, overview.

Thus the only difference between this situation and the other situations described before is that C_{Loss} does not represent an actual decrease of carbon pool sizes as before but an opportunity cost, a possible increase that does not take place.

The result for CN in Fig. 18 is almost identical to the result shown in Fig. 6, where the carbon balance of the initial decision to introduce energy production from biomass is shown. In summary, there would always be the alternative to stop removing residues and to 'refill' carbon pools, and this potential to refill carbon pools is not utilized when bioenergy production is continued (opportunity cost). Nevertheless, much more carbon can be 'saved' by continued energy production from logging residues than by refilling the soil carbon pools, because CN is positive from the very beginning (because C_{Bio} is at any time higher than dC_{Loss}).

4.3.2. *Substitution of oil instead of coal.* In the base case it was assumed, that the substituted fossil fuel has the same carbon emission rate per unit of heating value as biomass, which in an approximation means that coal is substituted. Fig. 19 shows results for the calculations with the assumption, that oil instead of coal is substituted. Oil causes about 20% less carbon emissions per unit energy than coal. Thus $C_{ref} = 0.8C_{Bio}$ and the formula for CN (for the base case Equation 3) becomes:

$$CN(t) = 1 - C_{Loss}(t)/0.8C_{Bio}(t).$$

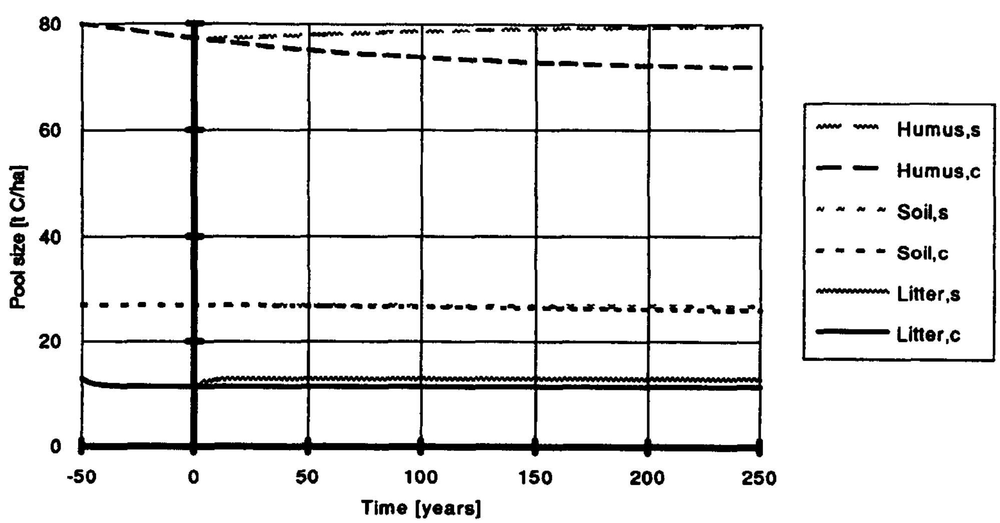

Fig. 16. Carbon pool sizes, continued (c) or stopped (s) energy production from logging residues.

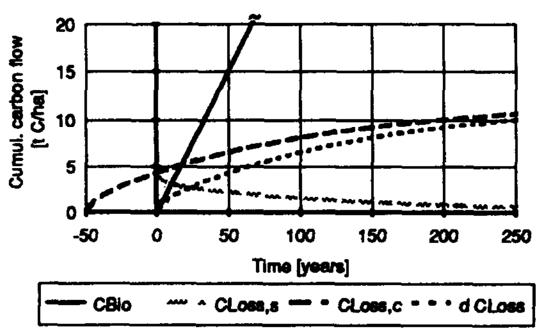

Fig. 17. Carbon in removed biomass, biospheric carbon losses for continued (c) and stopped (s) energy production from logging residues and the net difference (opportunity cost/dC_{Loss}).

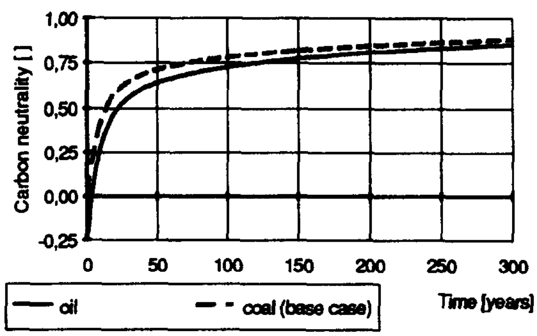

Fig. 19. CN with bioenergy substituting oil or coal.

Due to the factor of 0.8, the C_{Loss} term in this formula is higher than in the base case and thus CN is lower, beginning at -0.25, which can be explained as follows: 1 t of carbon in logging residues is taken away from a forest and is used to substitute 0.8 t of carbon in oil. So in the first year, 0.8 tC remain in fossil deposits while 1 tC is emitted from biomass burning. Thus, the carbon balance is negative in the first moment. It takes about 3 years for the carbon balance to be positive again. For substitution of coal, where bioenergy is converted with only 80% the efficiency of fossil fuel use, the results are the same: in year one, 0.8 tC remain in fossil deposits whereas 1 tC is emitted from biomass burning. These results emphasize that it does matter what kind of fossil fuels the biofuels are substituting, and that it is important to substitute efficiently.

5. RESULTS: LOGGING RESIDUES FROM CLEAR CUTTING

As far as the carbon dynamics in the forest floor is concerned, the main difference between selective harvesting and clear cutting is that there is an almost continuous litter production in selective harvesting, compared to a more 'batch-type' litter production in clear cutting. In Fig. 20, litter production for both cases is shown over time. High peaks for clear cutting illustrate the difference between the two cases. When whole-tree harvest is introduced instead of stemwood harvest, the steady-state litter production in the selective harvesting case is lowered from 2.7 tC ha^{-1} yr^{-1} to 2.4 tC ha^{-1} yr^{-1} as shown in Section 4. In the clear cutting case, the litter production during regrowth of trees remains the same, but the peaks due to felling are lower for whole-tree harvesting.

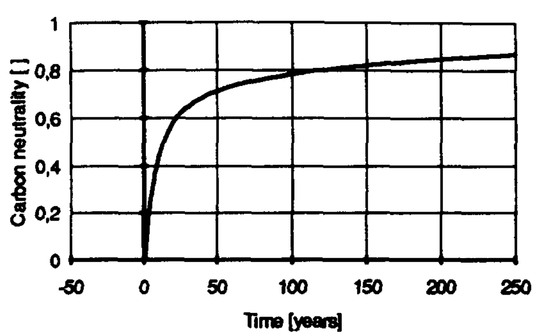

Fig. 18. CN for the carbon balance of the continued energy production from logging residues.

The model for calculating clear cutting strategies was calibrated in such a way, that the average litter production over the whole time period is the same as in the model for selective harvesting used in Section 4. The parameters κ and ϕ and the carbon pool sizes were not changed from the base case assumptions. It was necessary to include several parcels of forest in the model, because each year there is another parcel to be cut until the first parcel has regrown again. Thus, the number of years between two fellings on one parcel (in this case 100 years) equals the number of parcels to be considered in the model. Figure 21 depicts the results for CN, compared to the results from Section 4 (Fig. 6). It can be seen that there is almost no difference between the two curves, and thus it can be said that clear cutting strategies and selective harvesting strategies bring about the same results when calculations are performed with the model described in this study. However, there are several reasons that might cause the logging residues of a clear cut forest to decay faster or more slowly than of a forest under a selective harvesting regime:

- on a clear cut area there might be higher temperatures and therefore decay would be accelerated; or

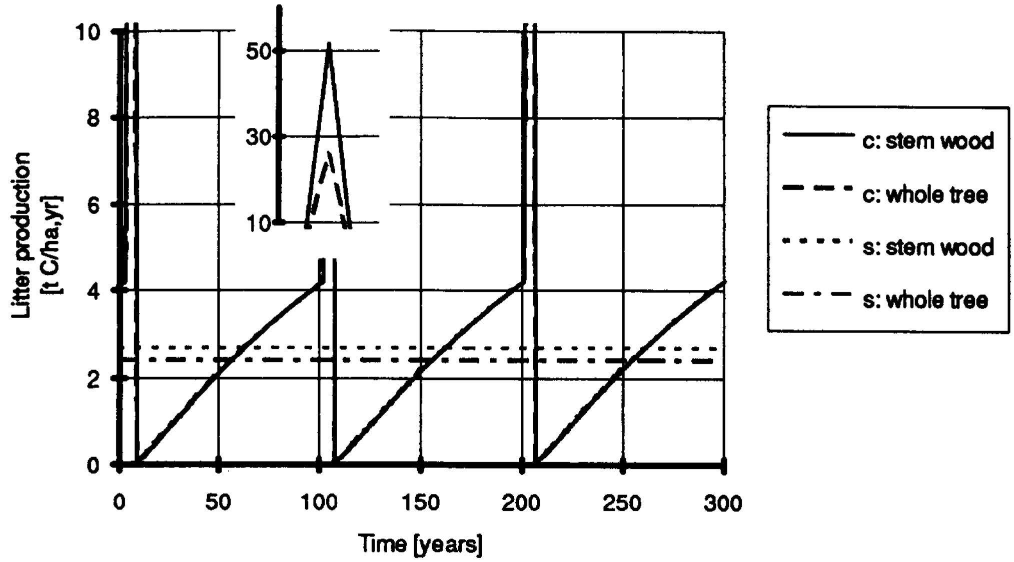

Fig. 20. Litter production for clear cutting strategies (c) and for selective harvesting strategies (s), for stemwood harvest and whole-tree harvest, respectively.

- the ground water level, and the humidity of the soil might be different, resulting in different decay rates.

These effects could influence the main parameters, but have not been considered in the calculations of this study.

6. COMPARISON TO OTHER STUDIES

Eriksson and Hallsby[20] made a carbon balance analysis of whole-tree harvesting strategies compared to stemwood harvesting for forests under clear cutting management. The logging residues that were left on the site in the course of stemwood harvesting are used for bioenergy when whole-tree harvesting strategies are introduced. The results of the Eriksson and Hallsby[20] analysis may be compared to the results of the study in hand, even though some assumptions are different. Eriksson and Hallsby[20] assume a rotation length of 100 years, just like in Section 5 of this study, and an amount of logging residues used for bioenergy of 40 t ha^{-1}, which corresponds to 0.4 t ha^{-1} yr^{-1}, whereas in this study 0.3 t ha^{-1} yr^{-1} are used. They further assume that the logging residues, if left on the site, decompose with a constant amount per year within 20 years, where in this study an exponential decay is assumed. They state, that "... in reality, the rate is probably faster in the beginning and slower in the end...". Eriksson and Hallsby[20] finally calculated biospheric carbon losses and amounts of substituted fossil carbon, both time dependent.

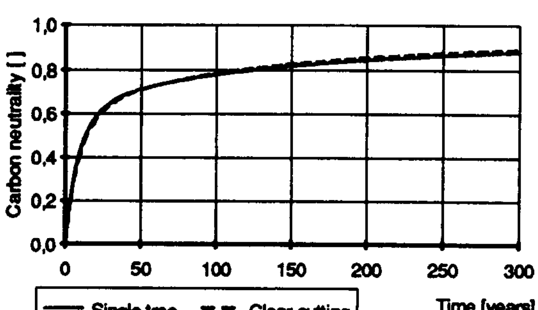

Fig. 21. CN of bioenergy from clear-cutting residues compared to selective-harvesting residues.

Eriksson and Hallsby[20] substituted oil in their calculations and therefore their amounts of fossil carbon have to be multiplied by 1.25 in order to be comparable to results of the study in hand assuming coal to be substituted. Using this factor and the numbers for C_{Loss} and C_{Bio} from Eriksson and Hallsby,[20] CN can be calculated in the same way as was done in Sections 4 and 5. The comparison is shown in Table 1. Results for CN derived from numbers in Eriksson and Hallsby[20] are low in the first 20 years, because they

Table 1. Comparison of results for CN derived from numbers in Eriksson and Hallsby[20] and from this study

	CN (20 years)	CN (100 years)	CN (300 years)
Derived from Eriksson and Hallsby	0.5	0.9	0.967
This study (Sections 4.1 and 4.2)	0.42–0.82	0.72–0.88	0.86–0.92

underestimate the decomposition rate of logging residues left on the site at the beginning. Later on (100 and 300 years) their *CN* is higher, because after 20 years decay of logging residues is finished for stemwood harvest and the authors do not include long-term effects on soil carbon storage into their calculations.

7. CONCLUSIONS AND OUTLOOK

Both energy related carbon fluxes (substituted fossil emissions, biomass removed for energy production) and carbon pool sizes in the biosphere must be taken into consideration when bioenergy strategies as a means to mitigate the rise of carbon dioxide in the atmosphere are evaluated. Model calculations show the extent to which substituting logging residues for fossil fuels is not completely 'CO_2 neutral'. Besides the avoided fossil carbon emissions there is a decrease of the carbon content in forest soils. One observation from the model output is that, over short time periods, capture of residues for bioenergy results in little to none, and perhaps even negative, savings of CO_2 emissions. It is only as the system is allowed to operate and come to an equilibrium that CO_2 savings begin to accumulate. CO_2 savings do highly depend on what kind of fossil fuels the biofuels substitute and how efficiently they are used.

In summary, the effect of soil and litter carbon emissions is limited, whereas biomass for energy can be harvested 'forever'. Thus net carbon losses of the biosphere represent a short-term effect compared to fossil fuel substitution. Fossil carbon emissions can be avoided to infinity and in a longer time perspective this effect exceeds by far the biospheric carbon losses.

Beyond this, it must be mentioned that, besides using logging residues, there are other bioenergy strategies which bring about fossil carbon substitution and additional storage of carbon in the biosphere coincidently leading to *CN* above 1 at the very beginning, for example a conversion of former agricultural areas for the purpose of short-rotation forestry.[21b] Recent work[6] includes carbon balances of other bioenergy strategies including short rotation forestry or herbaceous crops for heat and/or power production and non energy use of forest harvest for e.g. wood products. These analyses of bioenergy strategies include conversion efficiencies of biomass and of the substituted fossil fuels, so that complete carbon balances of bioenergy systems can be calculated.

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APPENDIX A: THE MODEL

The model to describe the carbon fluxes and pool sizes uses the following definitions:

L_o—carbon stored in the litter pool in equilibrium at time 0;
$L(t)$—carbon stored in the litter pool at time t;
H_o—carbon stored in the humus pool in equilibrium at time 0;
$H(t)$—carbon stored in the humus pool at time t;
S_o—carbon stored in the soil pool in equilibrium at time 0;
$S(t)$—carbon stored in the soil pool at time t;
LP_o—annual litter production in equilibrium at time 0;
$LP(t)$—annual litter production at time t;
NPP—annual net primary production;
RW—annual harvest of roundwood;
LRE—annual amount of logging residues for energy;
κ—share of the carbon flux out of the litter pool that enters the humus pool [$(1-\kappa)$ is emitted to the atmosphere];
ϕ—share of the carbon flux out of the humus pool that enters the soil pool [$(1-\phi)$ is emitted to the atmosphere];
k_{la}—carbon flux fraction from litter to atmosphere;
k_{ha}—carbon flux fraction from humus to atmosphere;
k_{sa}—carbon flux fraction from soil to atmosphere;
k_{lh}—carbon flux fraction from litter to humus;
k_{hs}—carbon flux fraction from humus to soil.

The system is assumed to be in an equilibrium at time 0. For that reason carbon fluxes in Scenario A (Fig. 2) can be calculated as linear functions of the litter production (LP_o):

$$LP_o = NPP - RW, \tag{A1}$$

$F_{lh,o}$ (Flux from litter to humus in equilibrium)

$$= \kappa \times LP_o, \tag{A2}$$

$F_{la,o}$ (Flux from litter to atmosphere in equilibrium)

$$= (1-\kappa) \times LP_o, \tag{A3}$$

$F_{hs,o}$ (Flux from humus to soil in equilibrium)

$$= \kappa \times \phi \times LP_o, \tag{A4}$$

$F_{ha,o}$ (Flux from humus to atmosphere in equilibrium)

$$= \kappa \times (1-\phi) \times LP_o, \tag{A5}$$

$F_{sa,o}$ (Flux from soil to atmosphere in equilibrium)

$$= \kappa \times \phi \times LP_o. \tag{A6}$$

In Scenario B (Fig. 2) carbon fluxes are not proportional to litter production as in Equations A2–A6 any longer, because the system is in a dynamic transition. According to Equation 4, carbon fluxes leaving a pool are proportional to the pool size.

$$LP = NPP - RW - LRE = LP_o - LRE, \tag{A7}$$

$$F_{lh} \text{ (Flux from litter to humus)} = L \times k_{lh}, \tag{A8}$$

$$F_{la} \text{ (Flux from litter to atmosphere)} = L \times k_{la}, \tag{A9}$$

$$F_{hs} \text{ (Flux from humus to soil)} = H \times k_{hs}, \tag{A10}$$

F_{ha} (Flux from humus to atmosphere)

$$= H \times k_{ha}, \tag{A11}$$

$$F_{sa} \text{ (Flux from soil to atmosphere)} = S \times k_{sa}. \tag{A12}$$

The following equations for the carbon mass balance of the three pools have to be solved:

$$dL/dt = LP_o - LRE - k_{la} \times L - k_{lh} \times L, \tag{A13}$$

$$dH/dt = k_{lh} \times L - k_{ha} \times H - k_{hs} \times H, \tag{A14}$$

$$dS/dt = k_{hs} \times H - k_{sa} \times S. \tag{A15}$$

With the initial equilibrium the proportionality factors k_{xy} can be calculated:

$$\begin{array}{ll} dL/dt = 0 & L = L_o \\ k_{la} = [(1-\kappa) \times LP_o]/L_o & k_{lh} = [\kappa \times LP_o]/L_o \\ dH/dt = 0 & H = H_o \\ k_{ha} = [(1-\phi) \times \kappa \times LP_o]/H_o & k_{hs} = [\phi \times \kappa \times LP_o]/H_o \\ dS/dt = 0 & S = S_o \\ k_{sa} = [\phi \times \kappa \times LP_o]/S_o. & \end{array}$$

Finally, with k_{xy} and Equations A13–A15

$$dL/dt = LP_o - LRE - LP_o \times (L/L_o), \tag{A16}$$

$$dH/dt = LP_o \times \kappa \times [(L/L_o) - (H/H_o)], \tag{A17}$$

$$dS/dt = LP_o \times \kappa \times \phi \times [(H/H_o) - (S/S_o)]. \tag{A18}$$

This system of differential equations with the unknowns $L(t)$, $H(t)$ and $S(t)$ can be solved numerically or analytically for given values for LP_o, LRE, L_o, H_o, S_o, κ, ϕ. The carbon emissions and CN (see Section 3.1) may now be calculated. According to Equation 3, $CN(t) = 1 - C_{Loss}(t)/C_{Bio}(t)$, where:

$$C_{Bio}(t) = LRE \times t, \tag{A19}$$

$$C_{Loss}(t) = L_o + H_o + S_o - L(t) - H(t) - S(t) \tag{A20}$$

and finally:

$$CN(t) = 1 - [L_o + H_o + S_o - L(t) - H(t) - S(t)]/(LRE \times t). \tag{A21}$$