GREENHOUSE GAS BALANCES OF BIOMASS ENERGY SYSTEMS

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Abstract

A full energy-cycle analysis of greenhouse gas emissions of biomass energy systems requires analysis well beyond the energy sector. For example, production of biomass fuels impacts on the global carbon cycle by altering the amount of carbon stored in the biosphere and often by producing a stream of by-products or co-products which substitute for other energy-intensive products like cement, steel, concrete or, in case of ethanol from corn, animal feed. It is necessary to distinguish between greenhouse gas emissions associated with the energy product as opposed to those associated with other products. Production of biomass fuels also has an opportunity cost because it uses large land areas which could have been used otherwise. Accounting for the greenhouse gas emissions from biomass fuels in an environment of credits and debits creates additional challenges because there are large non-linearities in the carbon flows over time. This paper presents some of the technical challenges of comprehensive greenhouse gas accounting and distinguishes between technical and public policy issues.

1. INTRODUCTION

To determine the full greenhouse gas implications of an energy system we would like to examine every phase of the system from resource extraction to waste disposal and evaluate the accompanying flows of greenhouse gases to and from the atmosphere. This includes the discharge of combustion products like CO_2 and the release of fugitive emissions like CH_4, but generally it means direct release of greenhouse gases during some phase of the fuel cycle plus emissions embodied in the materials of facility construction. For the purposes of this discussion we will focus only on the most important of the greenhouse gases, CO_2. For simplicity we will describe the flows of C, acknowledging that flows of C to and from the atmosphere are generally as CO_2. Our intent here is not to produce a detailed analysis of biomass energy systems but to illustrate the qualitative features of the carbon flows and to focus attention on a couple of components of the analysis which are particularly important for biomass systems. Biomass energy systems create a number of interesting accounting challenges that may be unique to biomass but focusing on them here may raise analogous issues for other energy systems. We will discuss 3 primary issues related to: 1) by-products of the energy system, 2) carbon standing in forests or other ecosystems and temporal variations in the net effect of biomass strategies on atmospheric CO_2, and 3) the possibility of both credits and debits in greenhouse gas emissions.

2. BY-PRODUCTS

Whereas many energy systems produce only energy products, biomass fuels are often produced along with other products. For example, combustible straw can be produced as a by-product of grain production, the dry milling process often used for producing ethanol from corn also yields distillers dried grains and solubles (DDGS - used as a protein-rich animal feed), and forest residues used as a fuel are often produced along with a wide range of lumber and pulp products. How then should we associate greenhouse gas emissions with the energy product as opposed to the other products? There are analogues in other fuel cycles as crude oil has non-energy as well as energy products and a hydroelectric dam provides non-energy services like flood control, irrigation, and recreation. The energy product may be a nearly incidental

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by-product, the primary product, or one of a slate of important products from a biomass harvest; whereas in the usual case of fossil fuels it is the primary product.

We illustrate this with a simple case, ethanol from corn, where the DDGS is clearly a by-product and the primary intent is to produce ethanol. Fig.1 presents the net benefit, in terms of CO_2 emissions to the atmosphere, when ethanol is used as an alternative fuel to motor gasoline. The carbon flows are based on current practice in the U.S. [1] where corn is planted with a diesel tractor, ground with electric power, distilled with a coal-fired furnace, etc. In this case we have assumed that by-product animal feed protein displaces an equal amount of protein which would otherwise have been supplied from soybeans, and have credited to the ethanol fuel cycle the fossil-fuel-based CO_2 which would have been released. There are other ways one might choose to represent the by-product credit and we suggest that the best choice may change when energy is not the dominant product as in the forest-harvest case, which we reserve for further discussion later.

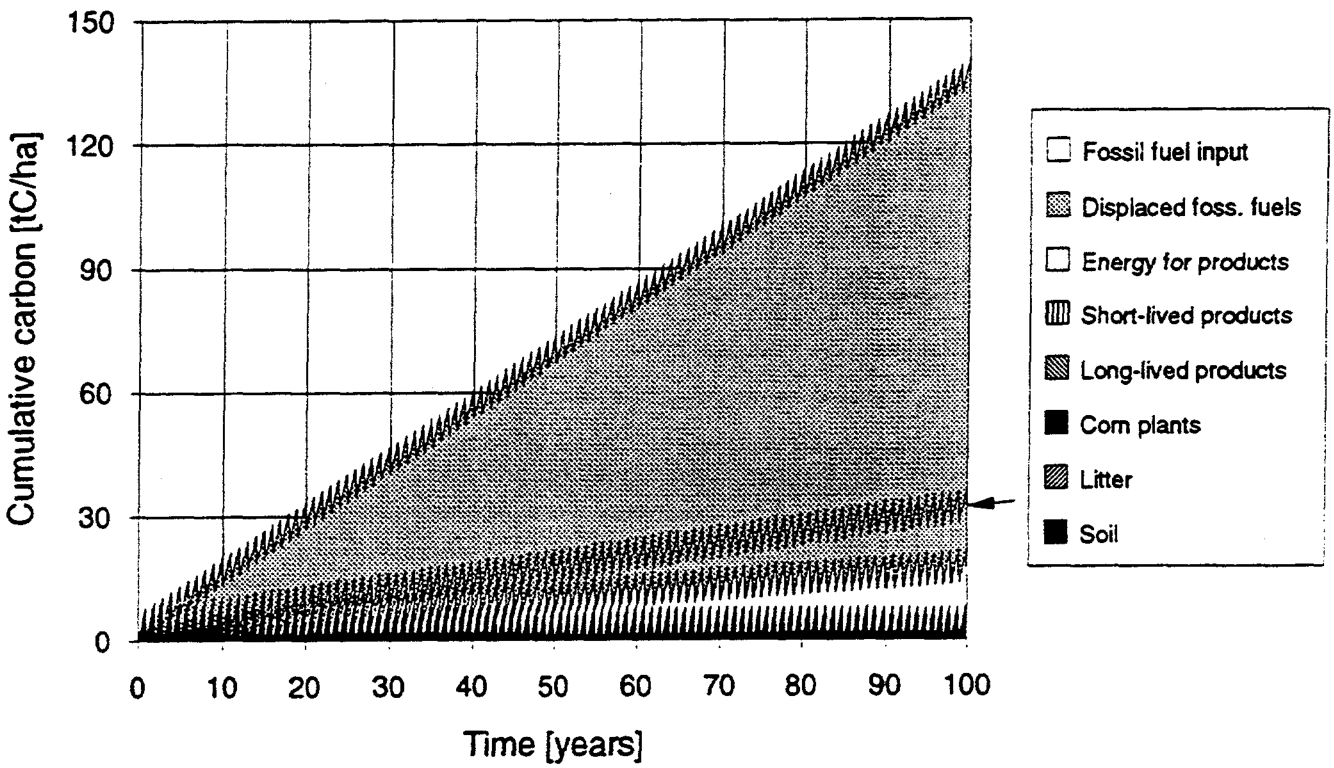

Fig.1. Net cumulative reduction in flows of carbon to the atmosphere when ethanol produced from corn is substituted for motor gasoline as a fuel. The various regions of the diagram show the increase with time in both carbon storage and carbon emissions avoided. Assuming that the land has been long used for agriculture there is no net change anticipated in soil or litter carbon and only a small amount of carbon is contained in the annual harvest of "trees" (in this case, corn plants). Assuming the feed protein is consumed promptly, there is no net storage of carbon in the by-products and thus "Short-lived products" and Long-lived"products" do not show in the diagram.. The two larger areas in the figure show the emissions avoided when ethanol is burned instead of motor gasoline and when the by-product animal feed is used instead of having to produce the same amount of protein from soybeans. What these areas do not represent is that there is a large input of fossil fuels (and CO_2 emissions) required for production of the corn and its conversion to ethanol. When we deduct the excess of C emissions for ethanol production with respect to the emissions when delivering gasoline from crude oil, the total net reduction in flows of carbon to the atmosphere is shown by the saw-tooth line indicated by the arrow to the right of the diagram [2].

As seen in Fig. 1, the data of Marland and Turhollow suggest that there is a benefit in net emissions of CO_2 to the atmosphere when ethanol is used in place of motor gasoline. However, the principal point which we want to make here is that the displacement of carbon emissions by a by-product of the energy system can play a major role in the net carbon balance.

The amount of fossil fuel used to produce ethanol from corn is very large and this raises another important point about biomass fuels. It is in principle possible to operate a bioenergy system with no net emissions of CO_2. For example, the production of ethanol from corn could use its own product ethanol to run equipment on the farm, for transporting materials, and for power generation. While this would create the appearance of very low CO_2 emissions per unit of output, it would have no net effect on the larger energy system. The overall effect would be to decrease the ethanol resource, that is, there would be less ethanol available in outside markets to displace other uses of fossil fuels. As long as ethanol provides energy at the margin of a large, fossil-fuel-based, energy system, we could use it to embellish the apparent emissions coefficients of its own fuel cycle but the net effect on total CO_2 emissions would not be affected. This principle can be generalized to state that the apparent impact of a fuel substitution can be made to appear differently depending on how we choose to define system boundaries and the kinds of numerics we select to represent emissions coefficients.

3. CARBON IN THE ECOSYSTEM

Forest management strategies can significantly affect the amount of carbon which is stored in both above-ground and below-ground living biomass and in forest litter and soils. For example, decisions to increase the production of wood fuel by decreasing the rotation length of forest harvest or by establishing a plantation forest on previously unforested land could, respectively, decrease or increase the amount of carbon stored in the ecosystem. In either case, analysis of the fuel cycle would need to consider this effect.

Figures 2 and 3 show the impacts, over time, on the net flux of CO_2 to the atmosphere when a short-rotation plantation is planted on land which was previously used for agriculture or grazing (Fig. 2) or when a conventionally managed forest is converted to a short-rotation plantation for woody fuel (Fig. 3). (See Ref. [2] for details of the figures and of the model on which they are based.) In Fig. 2 it is clear that there is a net accumulation of C in standing trees and in forest litter and soils and that these play a significant part in the net C balance, especially early in the project lifetime. For these illustrations we have selected what may be typical parameters anticipated for C accumulation in the ecosystem but analysis of any specific project would have to give careful consideration to both the current state of the ecosystem and to changes anticipated in C storage.

When a conventional forest is converted to a short-rotation, fuel-wood plantation we expect a decrease in the standing stock of carbon in all components of the ecosystem (Fig. 3). This decrease in C storage is a dominant feature of the net C balance during the early years of the analysis and emphasizes our point about the temporal variability in the C flux (see also Fig. 4). For any energy system there is some requirement for capital investment, e.g. facility construction, during which energy is consumed and CO_2 discharged with no immediate benefit in terms of services (energy) delivered. The consequence is that a long-term commitment to reducing CO_2 emissions might even result in a short-term increase in net CO_2 emissions. This temporal effect can be even more extreme for a biomass energy system and might come into consideration when short-term goals are set for CO_2 emissions. A biofuels project could end up as a net initial source of C to the atmosphere, as in Figs 3 and 4, before plantation growth and fossil-fuel displacement begin to compensate for an initial harvest. In cases of low forest productivity and/or efficiency in the use of the forest harvest, it might require very long times to return to the initial C balance and suggest against a biofuels project.

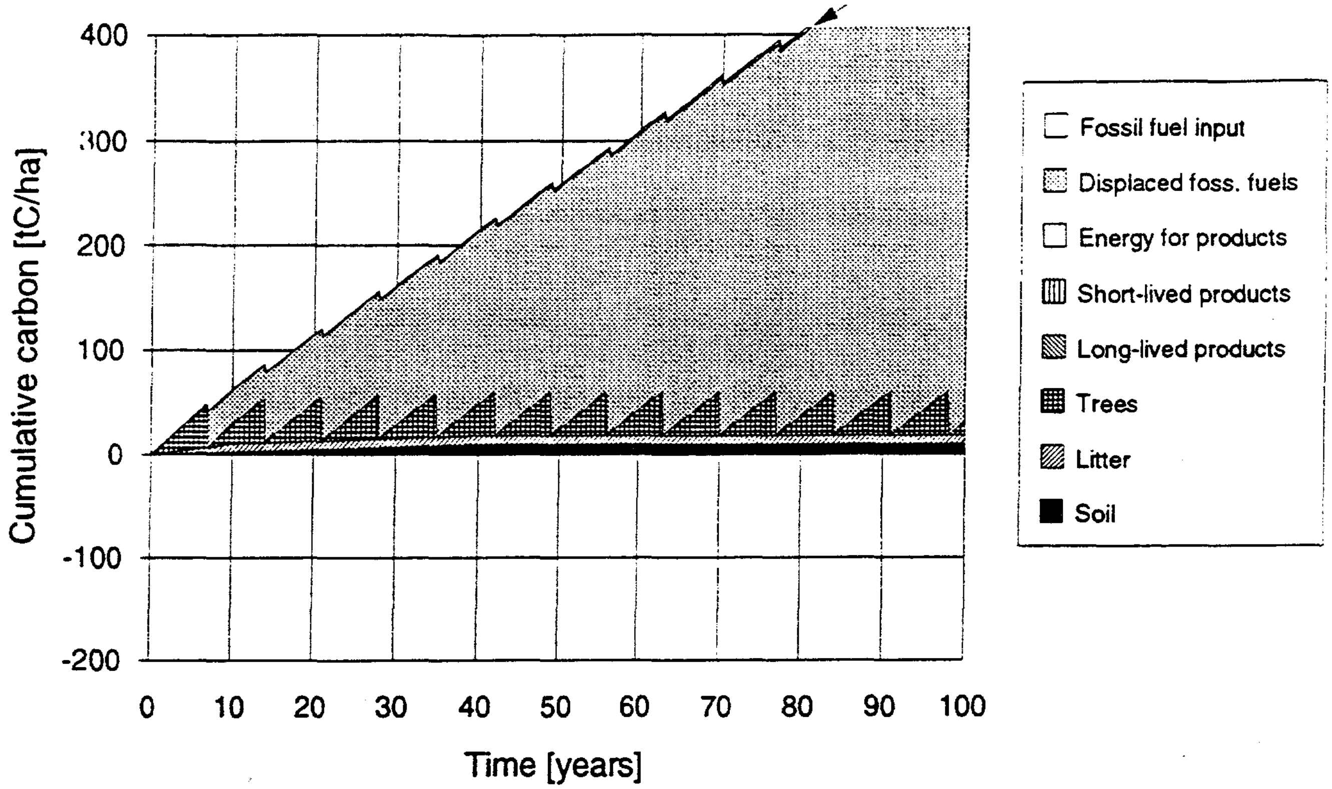

Fig.2. Net cumulative reduction in flows of carbon to the atmosphere when a plantation for a short-rotation woody crop is planted in an area previously occupied by agriculture and the harvest is used in a highly efficient way to substitute for coal for electric power generation. Some carbon is expected to accumulate in soils, forest litter, and in the standing trees but, over time, the dominant effect is the avoided fossil-fuel burning. The full harvest is used for power generation and no by-products are produced, so that "Energy for products", "Short-lived" and Long-lived products" do not show in the diagram. As in Fig.1, the fossil energy required for conversion of the biofuel is greater than for coal (only slightly so in this case) and the net reduction in emissions of carbon to the atmosphere is shown by the line indicated with the arrow on the right [2].

That a site currently occupied by forest can provide initially a source of greenhouse gas emissions yet eventually a sink is illustrated in both Figs 3 and 4. These figures capture another point relevant to consideration of by-products. Where durable wood products are a by-product, or co-product, of wood fuel production, a detailed analysis of C flows needs to acknowledge that the wood products avoid CO_2 emissions in 2 ways. They provide both a temporary (depending on the product lifetime) sink for C and the wood products displace other (usually) more energy-intensive products. In the illustration in Fig. 4, we have assumed that long-lived wood products have a mean lifetime of 60 years and substitute for concrete and steel in construction and that short-lived products with a mean lifetime of 15 years also have a similar effect on energy displacement. Over the initial decades the amount of C stored in (or released from) the ecosystem or in wood products dominate the net carbon balance but over time the role of fossil-fuel-combustion displacement, both directly and indirectly through product substitution, assumes a larger role.

In many biofuels scenarios the net flux of carbon will fluctuate greatly with time. As seen in Figs 3 and 4, there are major nonlinearities at not just an initial harvest, but at all subsequent harvests. For any policy decisions that rely on something like a carbon tax or short-term emissions-control targets this will require thoughtful consideration of how to deal with biofuels or other biomass-based mitigation strategies. It is interesting to note that whereas all 4 scenarios described so far produce net carbon benefits by the end of 50 years, there are striking differences

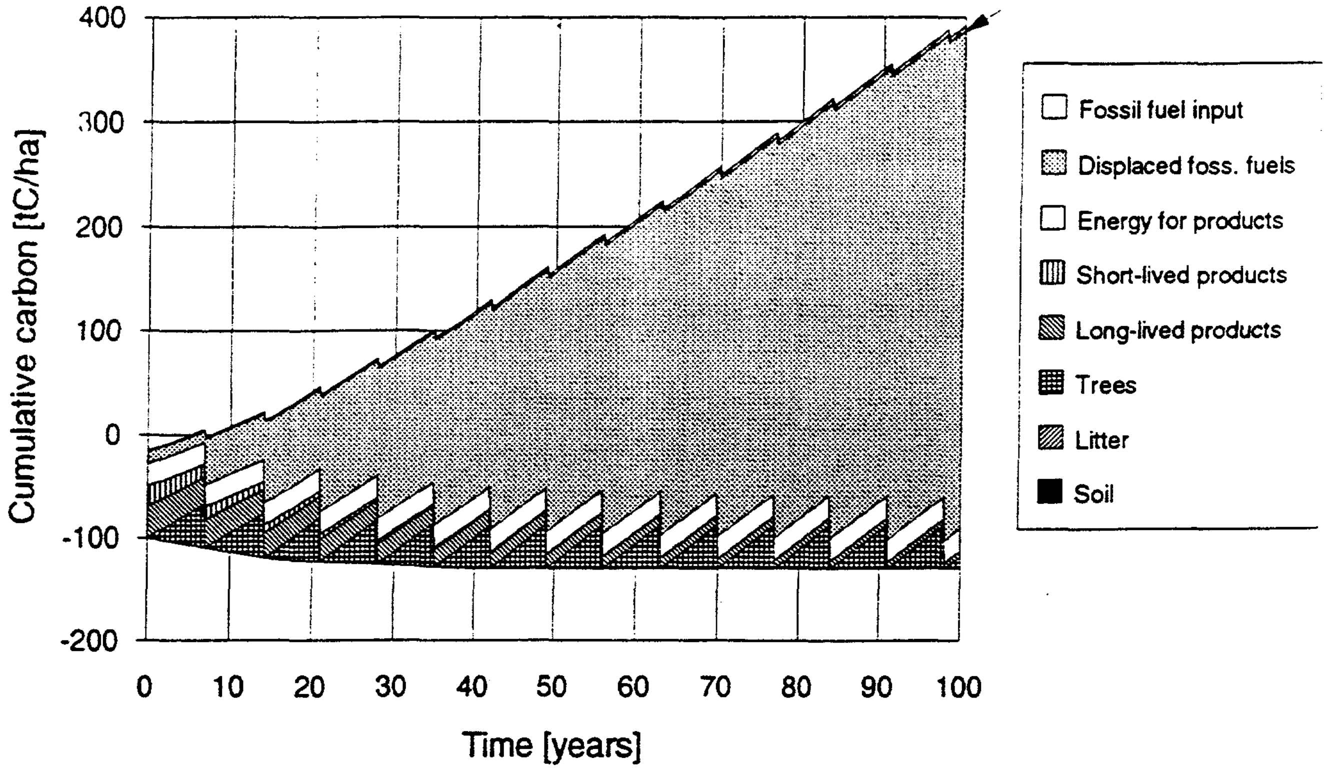

Fig.3. Net cumulative reduction in flows of carbon to the atmosphere when a forest of 100 t C ha^{-1} is replaced with a plantation for a short-rotation woody crop and the harvest is used in an efficient way to substitute for coal for electric power generation. The initial harvest is 100 t C ha^{-1} with part of the harvest allocated to wood products, but all subsequent harvests are used for energy only. The initial harvest results in a net decrease in the total of carbon stored in trees and durable products and, for the case modeled, there is a net initial emission of carbon to the atmosphere. This net initial emission is smaller than the decrease in C storage in trees and products because of the displacement of fossil-fuel burning (see text for explanation). This model run assumes that long-lived products have a mean lifetime of 60 years and short-lived products a mean lifetime of 15 years. The baseline of the diagram drops below the initial harvest loss of -100 t C ha^{-1} as some carbon is lost from soils and forest litter over time [2].

in the situation at the end of 20 years: +6 t C ha^{-1} for ethanol from corn, +110 t C ha^{-1} for the short-rotation plantation on agricultural land, +50 t C ha^{-1} for the short-rotation plantation on previously forested land, and -25 t C ha^{-1} for the conventional forestry with use of forest residues for fuel. Although these numeric values are very dependent on the set of parameter values we have chosen for these illustrations, the potential contrast between long-term and short-term achievements is clear.

The possibility of storing carbon in the ecosystem also suggests that if land resources are limited there is an opportunity cost associated with biofuels systems. When land is afforested there will be a net decrease in atmospheric CO_2 emissions whether or not the wood is harvested as a fuel. In fact, Fig. 4 shows a situation in which, over a considerable time, the opportunity cost in CO_2 is greater than the CO_2 benefit of the biofuels/wood products system and the forest is best left standing unless we are prepared to consider a project lifetime greater than 100 years. Using a very simple model Marland and Marland [3] have shown that with a 50-year planning time, the opportunity to store C in the trees exceeds the benefits of a biofuels system over a large range of circumstances (low growth rates and high standing biomass on the site). In summary, biofuels systems require a large resource commitment (land) and a greenhouse gas assessment should consider the opportunity for using the land in other ways to minimize net greenhouse gas emissions.

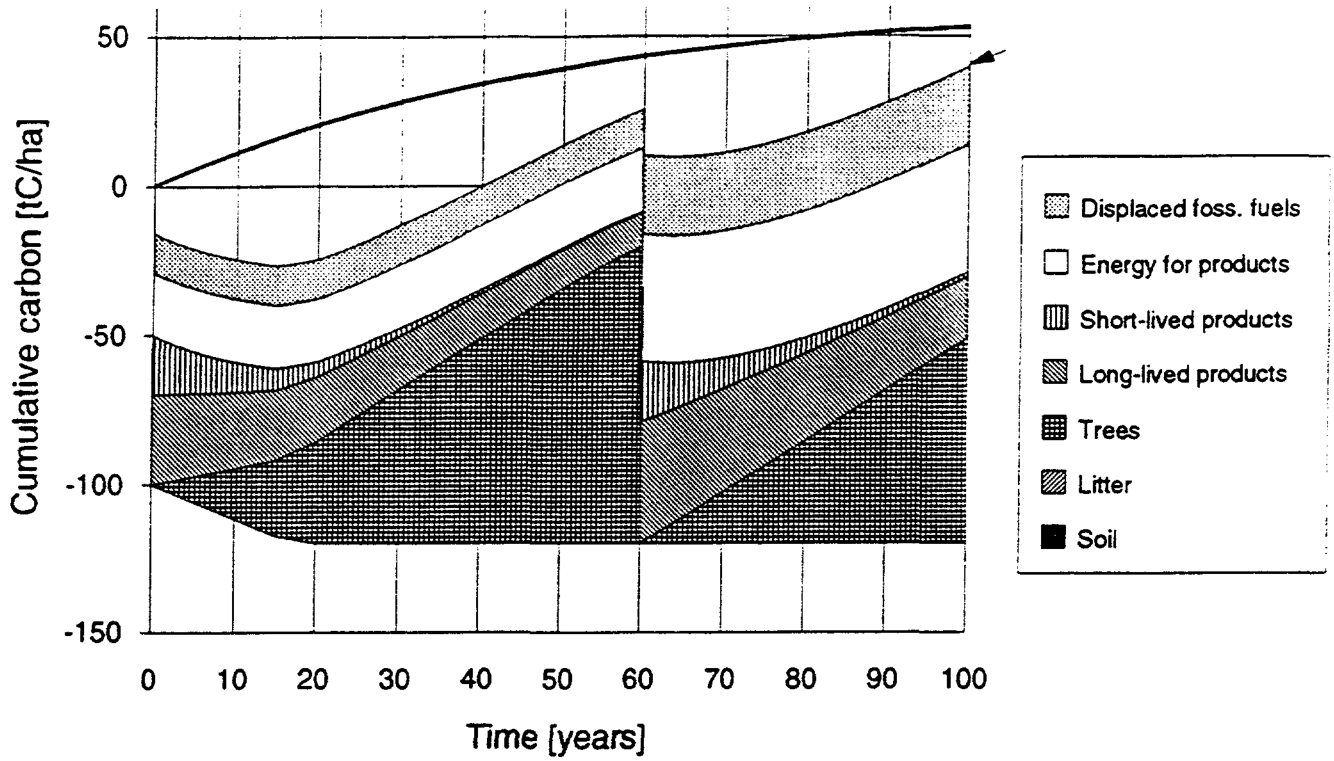

Fig. 4. Net cumulative reduction in flows of carbon to the atmosphere when forest residues from conventional forestry are used with modest efficiency to displace coal combustion. Input of fossil fuels for harvesting and processing of biomass has been neglected, because it is comparatively small. As in Fig.3, the model assumes that the initial harvest is 100 t C ha^{-1}; that the initial harvest is allocated among long-lived, short-lived, and fuel products; and that there will be some loss of C from soils and forest litter subsequent to the initial harvest. We assume that in the absence of a harvest the forest would have been capable of growing to a capacity approaching 160 t C ha^{-1} in 100 years (from Schlamadinger and Marland [2]), and a line showing the associated C uptake represents the opportunity for sequestering C. The figure shows that it takes 40 years before the net of carbon emissions to the atmosphere returns to zero and more than 100 years before the net of carbon emissions reaches what it would have been if the forest had been given the opportunity to continue growing.

Ultimately we confront the question, what is the greenhouse gas impact of a biofuels system based on a fuel like forest residues? This is essentially the other extreme in terms of the importance of product and by-products compared with the case for ethanol production described earlier. Based on the discussion above, our suggestion is that one needs now to compare against an alternate scenario where the residues are not used for energy. Figure 5 shows the net carbon flows when all of the details are as in Fig. 4 except that residues are returned to the forest. Acknowledging that the lifetime of forestry residues will depend on the climate, Fig. 5 assumes a mean lifetime of 15 years and shows that for the first 9 years net emissions of C are actually greater for the biofuels harvesting case because in this case the residues are burned promptly but are used to substitute for fossil fuels with only modest efficiency (i.e. using efficiencies similar to those that characterize current practice in the U.S.). Schlamadinger et al [4] made detailed calculations for the carbon balance from logging residues, based on a box model of litter and soil layers, and came to similar results.

It should be noted that the scenarios displayed in this paper are all based on C flows for a single unit of land (1 ha) which is treated as a homogeneous unit. If our objective is to manage a larger unit of land in order to maintain a constant flow of wood products or biofuels, the

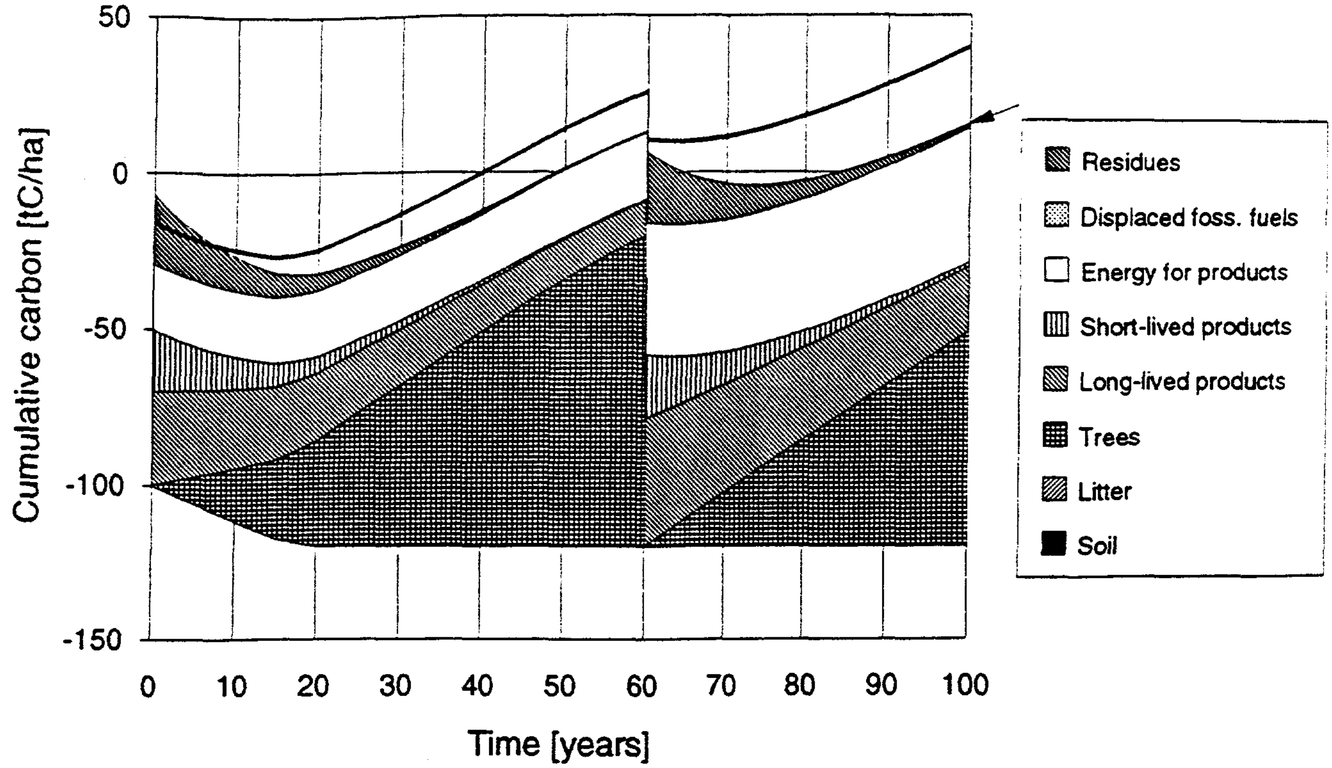

Fig. 5. Net cumulative reduction in flows of carbon to the atmosphere as in Fig. 4, except that forest residues are returned to the forest as litter rather than being gathered to substitute for coal combustion. Comparison with the black line (taken from Fig. 4) shows that net emissions of C may be less for the first few years but that over longer times the greater C benefit is achieved by harvesting and using the residues for energy.

short-term, initial characteristics of the C flow can be notably different depending on how the system is phased in. For example, the initial increase in net C emissions observed in Fig. 4 (i.e. negative values for cumulative net reductions in C emissions) may reach out to 70 years if we envision that 1 parcel of mature forest out of a larger system of 60 parcels is harvested each year and put into the 60-year rotation for producing wood products and bioenergy.

4. CREDITS AND DEBITS

Production of wood as a fuel involves relying on the photosynthetic process to remove C from the atmosphere and then burning the wood to extract useful energy while returning the C to the atmosphere. As discussed earlier, it is conceptually possible to design such a system with no net (over time) discharge of C to the atmosphere. With such a system, it is likely that there may be corporate or national boundaries that subdivide the system. Given then a political climate of credits and debits for greenhouse gas emissions, how should we allocate such credits if one party grows trees with the intent that they be used as fuel by another party? This transboundary accounting problem is equally relevant for the wood products industry generally. It is also likely that a biofuels system, with full fuel-cycle accounting, will generate a flow of carbon credits and debits that is very uneven over time. How then do we distribute credits over time when trees are grown with the intent that they will be harvested and used at some later time?

The problem here is again one of defining system boundaries and understanding all of the relevant processes which occur within the defined system. As described above and in Schlamadinger and Spitzer [5], for a complete and accurate accounting of the net carbon benefit of bioenergy systems we have to account for changes in the carbon stored in plants, plant litter, and soil; we have to account for the fossil fuels which are necessary to produce biofuels and convert them into useful energy; and we have to recognize that fossil fuels are displaced both by direct use of biofuels and by use of by-products. The balance of these accounts depends very much on the efficiency with which biofuels are produced and converted, the type of fuels which are displaced, and the efficiency with which the displaced fuels were or would have been used. For the accounting challenges described thus far, we can characterize the technical issues involved in a full and accurate representation. When there is interest in credits and debits we can primarily point out the kinds of issues which are uniquely relevant to biofuels and which will have to be confronted in a political context. It is a very different process to inventory emissions than to establish responsibility for them.

We describe 3 situations that involve harvest and use of wood with a likely net benefit in emissions of CO_2 to the atmosphere. In each case, however, the system boundaries are such that one part of the system experiences net carbon releases while another is neutral or has net carbon uptake. Our intent here is mostly to raise questions, as the answers lie largely in the political realm, but the key is that if we insist on assigning credits and debits, the accounting system should encourage both parties to participate in the process that produces the best result in summed carbon emissions.

(1) Party A harvests trees and sells wood fuel to Party B. The basic question is at what point the carbon is considered to be discharged to the atmosphere. Is it discharged to the atmosphere at the time the trees are cut, so that Party B gets an essentially carbon-free fuel while Party A gets all of the carbon debits; or is the carbon assumed to be discharged at the point of combustion so that Party A has no net carbon discharge (except for losses of soil and litter carbon) and Party B sees no carbon advantage in burning wood as opposed to coal? Party A controls whether the wood is from harvest of old-growth forest or from sustainable plantations and Party B controls how, and with what efficiency, the fuel is used.

(2) Party A harvests trees and sells wood products to Party B. When wood is used for durable products rather than as a fuel it no longer seems logical to consider that carbon is released at the time of harvest. However, if all of the carbon credits for sequestering carbon reside with Party B, Party A has no incentive for providing the renewable feedstock and might, in fact, incur debits for emissions from operating energy and losses from soils and forest litter, and perhaps for storing less carbon in the forest. Presumably party B should get credit for using wood rather than a more energy-intensive material such as aluminum?

(3) Party A pursues an afforestation project and gets credits for sequestering carbon. What happens when, at some future time, the forest is harvested for biofuels or wood products? Does it matter whether the products or biofuels are sold to another party as in items 1 and 2 above?

Many variants on these themes pose a challenge for any system of credits and debits. Can a system assure that wood fuels and wood products will be used in the most advantageous and efficient manner? Is a flow of credits and debits or of money necessary between parties in exchange for the flow of carbon in biomass and how should it be determined?

5. SUMMARY

Accounting for emissions and sinks of greenhouse gases over the full fuel cycle is a challenging task for any fuel cycle. For fuel cycles which involve biomass fuels there are some additional accounting problems because biomass fuels are often produced along with other non-energy products and because producing and harvesting biofuels involves associated changes in the storage and flows of C in the biosphere. Using a simple model of carbon flows we have tried to describe the implications of the decision to use biofuels. The output from this model suggests that substituting biofuels in place of fossil fuels can make a contribution to ameliorating the atmospheric increase in CO_2 but that producing biofuels is not necessarily the best choice under all circumstances and that there are significant differences among alternative approaches. It is necessary to examine the specifics of particular cases, the opportunity costs for committing land resources, the fossil-fuel-based system that would be replaced or used as an alternative, and the efficiencies which would characterize the alternatives. In particular, biofuels scenarios need to examine the disposition of any initial harvest, the growth rates which can be expected in subsequent cycles, and finally - as a consequence - the characteristics of the total net effect on atmospheric CO_2 as a function of time.

The characteristics of biofuels scenarios need to be considered in terms of the ultimate objectives, like preventing climate change, because various schemes for emissions credits, debits, and short term targets may conflict with what are, over the long-term, the most attractive choices in terms of net carbon flows. And, the discussion here is based only on CO_2. Ultimately we should give some consideration to CH_4, N_2O as greenhouse gases, and perhaps to species that influence the oxidation chemistry or particulate burden of the atmosphere. For biofuels projects a full and complete analysis of the full fuel cycle creates some interesting accounting challenges, but it is very important that the balance of credits and debits be clearly understood.

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