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Net effect of forest harvest on CO_2 emissions to the atmosphere: a sensitivity analysis on the influence of time

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ABSTRACT

Forests can be harvested and regrown on a sustainable basis while harvested material is used to either store carbon in long-lived wood products or to displace carbon dioxide emissions from fossil fuel combustion. To frame the question whether this implies that harvesting forests is an effective strategy for mitigating the increase of carbon dioxide in the atmosphere, we use a carbon accounting model to ask how long it takes to return to the original carbon balance after a forest stand is clear-cut harvested for biofuels and other forest products. Although the numerical solution depends on a great variety of site-specific model input parameters, it is clear that the system will not return to its original carbon balance for a very long time (perhaps centuries) unless forest products are produced and used efficiently. Especially when the cycle of producing forest products involves initial harvest of a forest stand with a large standing stock of biomass, there is likely to be a long-standing debit in terms of net carbon emissions to the atmosphere. On the other hand, if forest harvest is produced and used with high efficiency and the rate of regrowth is high, potential carbon benefits can be very high over time and it is possible that there is never a carbon debit with respect to forest protection, even immediately following harvest. Any intent to use forest harvesting to help mitigate the buildup of carbon dioxide in the earth's atmosphere should be able to demonstrate that the forest regrowth and product use can compensate for the loss of carbon from the forest as a result of the initial harvest.

1. Introduction

Forest management is among the alternatives frequently cited as a measure to mitigate the accumulation of CO_2 in the earth's atmosphere. Forest management can reduce the net flux of C to the atmosphere through reforestation and increased sequestration of C in forest biomass or by simple protection of the C that is already stored in the living and dead biomass of existing forests. Forest management can also mitigate the net flux of CO_2 to the atmosphere to the extent that C is stored in forest products or that sustainable harvest of biofuels or forest products displaces the use of fossil fuels. Does it then make sense, in terms of C flows, to clear-cut harvest mature forests in order to put the forest land into a harvest cycle for production of forest products? Harmon et al. (1990) show that it can require hundreds of years after harvest for old-growth forests in the North-West USA to return to the initial C balance, but they do not include consideration of fossil-fuel emissions that are saved because of biomass fuels and the use of forest products. Using a carbon accounting model of the full forest/forest-products system we examine how

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the rate of forest regrowth, the efficiency of forest product production and use, and the initial standing stock of the forest influence the time required to return to the initial net C balance (with respect to the atmosphere) or to achieve other objectives. Neither Harmon et al. (1990) nor we in this paper consider that natural disturbances can create a dynamic net flux of carbon to and from the atmosphere over time.

2. Methods

In this study we apply the model GORCAM (Graz/Oak Ridge Carbon Accounting Model; see Schlamadinger and Marland, 1996), a spreadsheet tool for calculating the time-dependent C flows and stock changes associated with land use, land-use change, forest management, and biomass use for products and fuels. The details of the model are described in Schlamadinger et al. (1998) and at www.joanneum.ac.at/gorcam.htm. The model calculates C accumulation in plants, in long and short-lived wood products, in fossil fuels not burned because biofuels are used instead, and in fossil fuels not burned because production and use of wood products requires less energy than does production and use of alternate materials that provide the same service.* The model requires parameters to describe: the initial carbon storage on the site, biomass growth rates, the rotation period, the allocation of forest harvest to various product and waste streams, the mean lifetime of wood products and of soil and litter C, the efficiency with which wood products are used (and comparable values for the materials they displace), and the energy required for the management of the forestry system (and comparable values for production and delivery of alternate fuels or products). Wood materials can be recycled, placed in a landfill, or used to generate energy at the end of their useful lives. The version of the model employed here uses a simple growth function for trees (Marland and Marland, 1992) and a dynamic representation for the transfer of C to and from the litter and soil C pools (Schlamadinger et al., 1998; Dewar, 1991).

The approach here is to define a series of scenarios and to examine in two-dimensional plots the net carbon balances as a function of time. We then isolate important parameters and show in three-dimensional plots how the net C balance over time depends on the specific values of these important parameters. These sensitivity analyses ultimately help us to recognize that for many of the parameters there are threshold values below which the management regime should not be carried out at all, if the carbon balance is a primary concern. Also, we see that there are parameters where optimization can help a lot to improve the system's C balance and that, sometimes, optimizing one parameter only makes sense when other parameters exceed certain threshold values.

In this paper, we focus on carbon issues, acknowledging that carbon is only one of the criteria upon which forest management decisions will be based. Other considerations, such as nutrient balances, biodiversity issues, impacts of possible future climatic changes on forests, or economic aspects, will play crucial roles in determining strategies for forest management.

3. Scenario assumptions

Using the model GORCAM, we ask how long it takes for the net C sequestered to return to its initial balance when standing forest is harvested for products and then promptly replanted. The rotation period in all base-case scenarios is assumed to be 60 years with a growth rate of tree biomass of 1.72 MgC ha^{-1} yr^{-1}. Harvest occurs at 100 MgC ha^{-1} when the growth rate is used as a sensitivity variable.

We are interested in the time interval required for the carbon balance of a harvested forest to return to the value it would have had without clear-cut harvest. We acknowledge that even in the absence of a harvesting regime there can be natural mortalities (such as fire or insects) that can diminish the carbon storage. Our analyses do not take into account such events, but consideration of natural mortalities would likely shorten the time required for harvesting and replanting of forests to show a positive net carbon sequestration effect.

We perform sensitivity analyses (see Table 1 for

* One key assumption is that additional forest harvest implies greater use of forest products in construction or the energy sector.

Table 1. *Overview of figures and analyses*

Fig.	Description of situation analysed		Rate of regrowth ($MgC\ ha^{-1}\ yr^{-1}$)	Efficiency factor	Initial C in tree biomass ($MgC\ ha^{-1}$)
	Net carbon balance as a function of key parameters				
1	Afforestation scenario	Scen	1.72	1	0
2	Scenario with harvest of densely stocked forest (extreme case with 300 $MgC\ ha^{-1}$)	Scen	1.72	1	300
3	Sensitivity to initial standing stock. The scenarios in Figs. 1, 2 represent the extreme cases in this diagram	SA	1.72	1	0 to 300
4	Sensitivity to rate of regrowth; a mid-range value of 160 is used for initial standing stock	SA	0 to 5	1	160
5	Scenario as part of Fig. 4, with growth rate set to zero; this represents deforestation, with slash left on-site	Scen	0	1	160
6	Sensitivity to efficiency of product production and use	SA	1.72	0 to 2	160
	The choice among forest management alternatives				
7	As Fig. 4, but the initial C stock is 100 $MgC\ ha^{-1}$ and there is continued forest growth (i.e., no harvest)	SA	0 to 5	no harvest	100
8	As Fig. 4, but the initial C stock is 100 $MgC\ ha^{-1}$	SA	0 to 5	1	100
9	The difference between the results in Figs. 7, 8	SA	0 to 5	–	100
	Discounting the future				
10	As Fig. 3, but future carbon stock changes are discounted with a discount rate of 4%	SA	1.72	1	0 to 300

"Scen": individual scenario; "SA": sensitivity analysis. The range of values for the rate of regrowth and the initial on-site carbon has been chosen based on forest carbon data for the US (Birdsey, 1996), and data on mean annual increment from Nilsson and Schopfhauser (1995).

an overview of the scenarios examined and the related figures in this text) to show the impact of varying (1) rates of regrowth, (2) the efficiency with which the harvest is used and (3) the amount of carbon stored on the site initially; on the time period after which the total C balance returns from a net source to a net sink (or reaches an intended level). The "efficiency factor" is a proxy for many of the model input parameters, including the amount of fossil fuel replaced by 1 ton of carbon in biofuel and the amount of fossil fuel substituted because wood replaces other, more energy intensive materials. It also includes the lifetime of wood products and the share of waste-wood that is incinerated to produce energy (which otherwise would have been generated using fossil fuels). The default value for the "efficiency factor" is 1, representing a situation where 1 MgC of biofuel replaces 0.6 MgC of fossil fuel (Marland and Marland, 1992), where 1 Mg of carbon in long-lived wood products — displacing products from non-wood materials — results in a fossil-fuel emission reduction of 0.5 MgC in product manufacture, and where 1 MgC of carbon in short-lived wood products reduces fossil-fuel emissions by 0.25 MgC (Schlamadinger and Marland, 1996). These values of the efficiency factor are applied to any initial harvest at time zero. For future biomass use it is assumed that the efficiency factors are somewhat greater due to technological development: 0.8 for biofuels, 0.8 for long-lived wood products and 0.4 for short-lived wood products. The mean lifetime of wood products is taken to be 30 and 10 years (for long-lived and short-lived products). 30% of waste wood products is used to generate energy as heat or power, and 1 MgC in waste wood products displaces 0.6 MgC of carbon in fossil fuels. An efficiency factor of 2 indicates that all of these parameters have been multiplied by 2 whereas an efficiency factor of 1/2 indicates that all of these parameters have been divided by 2. The efficiency factor provides a collective indication of the efficiency with which forest products are produced and used.

The GORCAM model also considers fossil fuel inputs for forest management, biomass transportation and conversion. Fossil fuels also require some additional energy to produce them, so that in many cases the auxiliary energy inputs of biofuels/wood products and the auxiliary input of fossil fuels nearly cancel out in the analyses. The absolute numbers are generally one order of magnitude smaller than carbon in harvested wood and in displaced fossil fuels (Karjalainen and Asikainen, 1996), and we have not considered auxiliary energy in this paper. Auxiliary energy can be an important component in systems for production of liquid biofuels, such as ethanol from corn (Marland and Schlamadinger, 1995).

4. Analysis

4.1. Net carbon balance as a function of key parameters

The basic model results are shown in diagrams with changes of C stock sizes over time. The sum of all changes in carbon stocks indicates the net C discharged to or taken up from the atmosphere. Figs. 1 and 2 show the results for two scenarios with extreme values for the initial standing stock, an afforestation scenario starting with agricultural land and a scenario with initial harvest of forest with 300 MgC ha^{-1} in living tree biomass (a very high but still possible number, see Birdsey (1996) and Adams (1997)). For comparison both diagrams have the same scale on the vertical axis. As in the scenarios that follow, many parameter values have been assumed in order to generate these illustrative scenarios; so the final output should be taken as illustrative rather than demonstrative and focus should be on the sensitivity to key parameters.

In the afforestation scenario (Fig. 1) soil and litter carbon pools increase in size from the beginning. The growing trees sequester carbon until harvest at time 60, when the carbon is partly diverted into wood products of varying lifetimes (30% of the harvest to long-lived products and 25% to short-lived products) and partly burned to produce heat and/or electricity (22% of harvest), with the remaining carbon (23%) left on the site to decay. "Displaced fossil fuel" in the figure represents the amount of fossil fuel not burned because biofuel is used in its stead. "Energy for products" includes emissions saved when wood products replace products from more energy intensive materials such as steel, concrete or glass (Schlamadinger and Marland, 1996).

The cumulative changes of C stocks in Fig. 2 are shown starting at the bottom line of the diagram (-300 MgC ha^{-1}), because that is the amount of C that was stored in living trees prior to the initial harvest. Part of that carbon is left on the site and added to the soil and litter carbon already there to decompose as slash, the remainder being diverted to wood products or biofuel, as in Fig. 1. In the longer term the C stored in soil and litter follows a decreasing trend as oxidation exceeds C flows into these pools. As stated in Cooper (1983), tree biomass in managed forests,

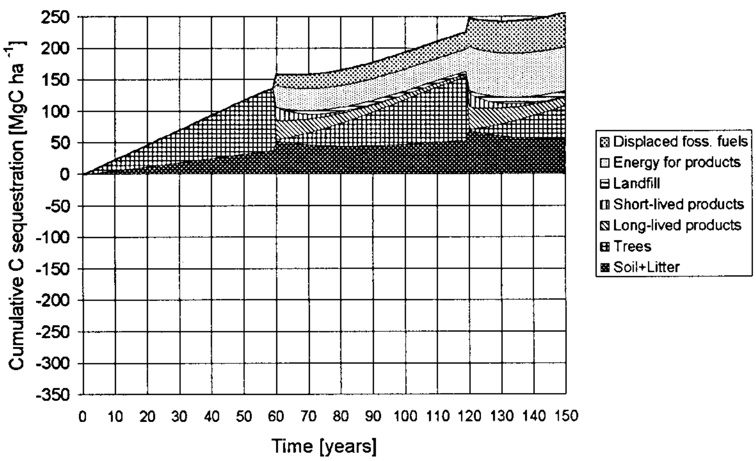

Fig. 1. Basic GORCAM results for a scenario with afforestation of agricultural land to produce wood products and biofuels.

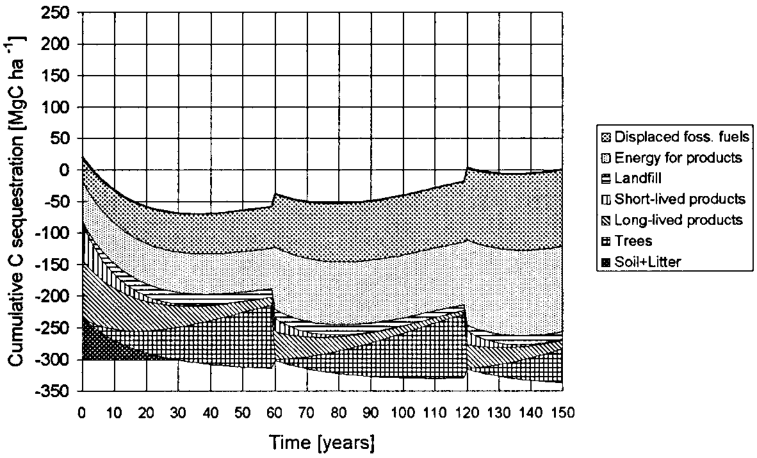

Fig. 2. Basic GORCAM results for a scenario with harvest of 300 MgC ha^{-1} where the land is subsequently managed for wood products and biofuels. After the initial harvest all parameters are as in Fig. 1.

when averaged over time, stores considerably less carbon than in unmanaged forests that are in steady state. It takes a very long time, here 120 to 150 years, until the total C storage returns to its initial value. Only after more than 150 years does harvest result in a gain for the atmosphere in terms of the net carbon balance.

By performing several model runs, as in Figs. 1 and 2, with varying initial on-site carbon, we generated the three-dimensional diagram of model output in Fig. 3. The right diagram of Fig. 3 provides a 2-dimensional contour plot of the same information in order to make the shape and location of the zero contour more clear. The very front line of the 3-dimensional diagram (at "initial above-ground C" equal 300) exactly matches with the upper line in Fig. 2, and the very back line (at "initial above-ground C" equal 0) exactly matches with the upper line in Fig. 1. The scale for "initial above-ground carbon" in Fig. 3 has been reversed in order to make the surface more visible.

One observation from Fig. 3 is that (for the set of parameters chosen) only harvest of forest stands with less than 120 MgC ha^{-1} yields positive results for savings of net C emissions to the atmosphere from the very beginning. In general, at any time within the analyzed time period, the total net C sequestration is the greater, the smaller the initial C storage (the only exception to this is at time zero). In other words, the front of the surface in Fig. 3 is lower than the back.

When forest is harvested some carbon is released to the atmosphere from decay of slash, from burning of fuelwood, and, over time, from oxidation of wood products. This loss of C to the atmosphere is at least partly offset by avoided emissions from fossil fuels, and, over time, by regrowth of the forest. The more C on the site initially, the longer it takes to return the net C balance to the initial value.

Whereas Fig. 3 shows the sensitivity of the carbon balance to the initial standing stock, Fig. 4 depicts the sensitivity to another important parameter, the rate of forest regrowth. In Fig. 4, the initial C storage was kept at 160 MgC ha^{-1} with the assumption that this represents mature forest with no expected change in C storage over time. For the sake of illustration we ignore the dynamics of carbon variability that may occur due to natural fluctuations and disturbances. The growth rate was varied between 0 and 5 MgC ha^{-1} yr^{-1}. Note that when the rate of forest regrowth following harvest is low (less than about 0.5 MgC ha^{-1} yr^{-1}), the time required to return to the original C storage is greater than 150 years, even when full consideration is made of C storage in products and displacement of fossil fuel use (Fig. 4, arrow 1). The higher the growth rate, the shorter the time after which a positive net C sequestration is achieved. For example, with a growth rate of 1.5 MgC ha^{-1} yr^{-1} the C balance is zero after 40 years (arrow 2) and increases thereafter, so that after 100 years the net C sequestration is at

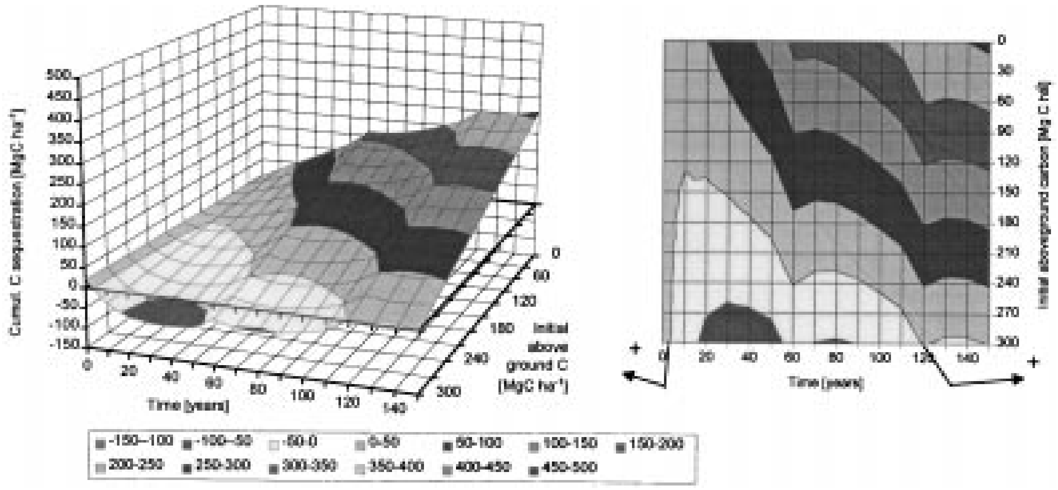

Fig. 3. Total cumulative carbon sequestration as a function of time and of the carbon stored on the site prior to harvest. "Cumulative C sequestration" considers on-site carbon storage as well as storage in wood products and credits for fossil fuel displacement, here at high but not extraordinary efficiency (efficiency factor equal 1). The diagram on the right is a contour plot of the 3-dimensional diagram on the left.

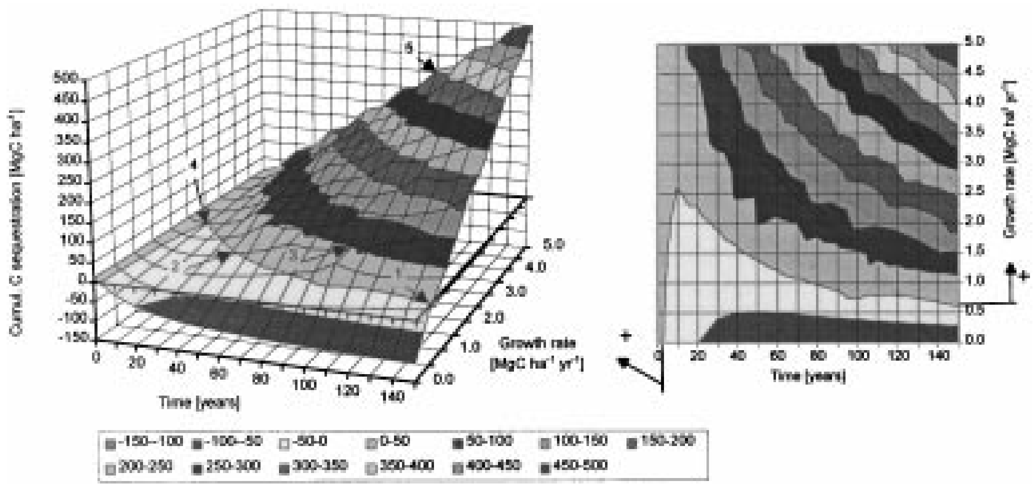

Fig. 4. A forest stand with an initial standing stock of 160 MgC ha^{-1} is harvested at time = 0 for conventional wood products and biofuels. The forest regrows at the growth rate given on the axis on the right side of the diagram and is harvested each time the standing stock is at 100 MgC ha^{-1}. As in Fig. 3, both the 3-dimensional diagram (left) and the contour plot (right) are shown.

50 MgC ha^{-1} (arrow 3). For growth rates greater than 2.5 MgC ha^{-1} yr^{-1} the C balance is at positive values from the very beginning (arrow 4) and with very high growth rates (5 MgC ha^{-1} yr^{-1}) the C mitigation effect can be as high as 350 MgC ha^{-1} after 100 years (arrow 5).

Fig. 5 shows the cross-section through Fig. 4 where the rate of regrowth is set to zero. This is shown separately because it represents the special case where a stand is cleared but not replanted. This scenario differs from a deforestation scenario because here the wood is assumed to be used for wood products and biofuels, and the slash is left on the site to decay. In a typical deforestation

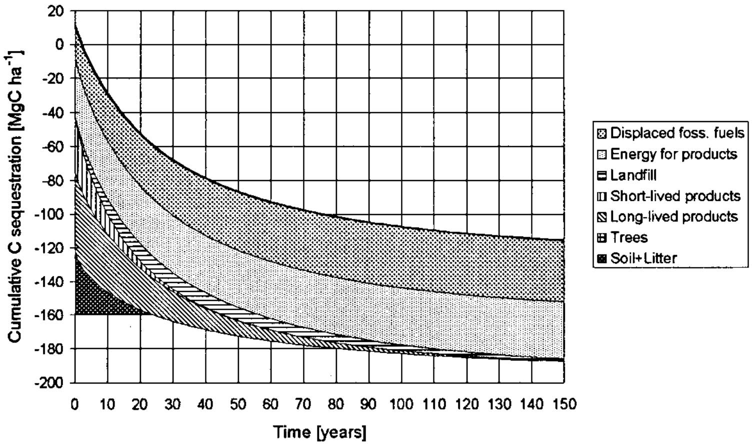

Fig. 5. Details of the cross-section through Fig. 4 when the rate of regrowth is zero, i.e. when forest is harvested but not allowed to regrow.

scenario the slash, or even all of the material, is often burned with immediate release of C to the atmosphere with perhaps a fraction of the carbon left as long-lived charcoal. The C balance is at negative values almost from the very beginning. It decreases further gradually, as the carbon in slash and in products is released over time. The credit for saved fossil fuels is the only part of the C balances that is preserved "forever".

A 3rd set of parameters that is very important in governing the net C balance describes the efficiency with which forest products are produced and used. For simplicity we have aggregated this large set of parameters into a single parameter identified as the "efficiency factor" as defined above. Fig. 6 shows the sensitivity to the efficiency factor when the growth rate is held at the baseline value of 1.72 MgC ha^{-1} yr^{-1} and the initial standing stock is set at 160 MgC ha^{-1}, as in Fig. 4.

When forest products are used inefficiently or otherwise do not significantly displace fossil-fuel consumption, very long times can be required to return to original C storage, even when growth rates are reasonably high at 1.72 MgC ha^{-1} yr^{-1} (Fig. 6). However, substantial C mitigation can be achieved over time when both growth rate and efficiency of fossil-fuel displacement are high.

4.2. *The choice among forest management alternatives*

The scenarios described to this point all consider the absolute value of the carbon balance as a function of some of the key parameters that will determine that balance in any given situation. In those cases where the initial condition is not a forest in steady-state, but still sequestering carbon from the atmosphere, there are management alternatives that could lead to significantly different outcomes in terms of net carbon emissions. For example, given a set of physical parameters for a forest stand, is it more advantageous (in carbon terms) to harvest the forest for wood products or to protect the existing forest to take up more carbon from the atmosphere?

We consider the specific case of a forest stand with 100 MgC ha^{-1}. Given the choice of harvesting this stand for a conventional mix of forest products or of protecting the stand so that it will continue to grow and take up carbon (with a maximum sustainable storage of 160 MgC ha^{-1}), how does the management choice depend on the expected rate of forest regrowth?

Fig. 7 shows the result for a forest protection scenario when the rate of forest growth ranges from 0 to 5 MgC ha^{-1} yr^{-1}. But these growth rates characterize the young, vigorously growing stands and the growth rates at a C storage of 100 MgC ha^{-1} are lower as the stands mature and approach a steady state carbon-balance (at 160 MgC ha^{-1}). Fig. 8 starts with the same forest stand of 100 MgC ha^{-1} at time zero, with the stand immediately harvested and replanted. Given these two scenarios we can represent their relative benefits.

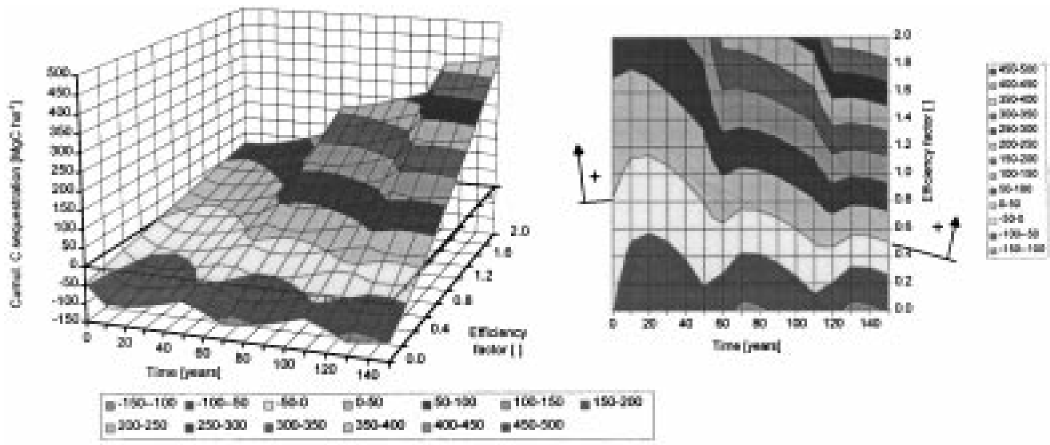

Fig. 6. Total cumulative carbon sequestration as a function of time and of the efficiency with which forest products are produced and used. As in Figs. 3 and 4, both the 3-dimensional diagram (left) and the contour plot (right) are shown.

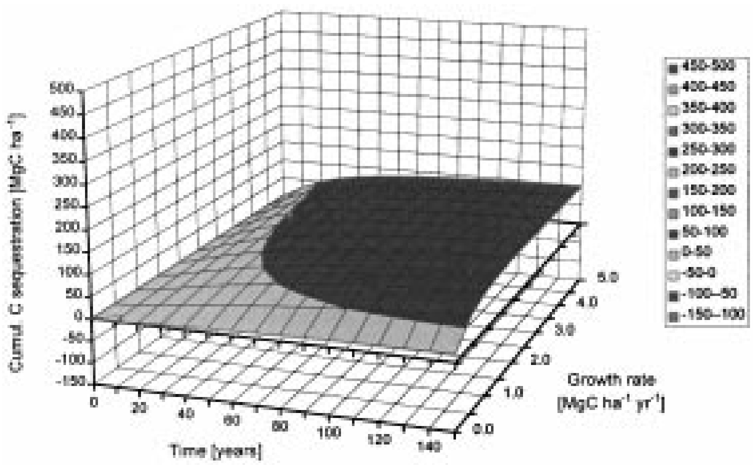

Fig. 7. Protection of an initial standing stock of 100 MgC ha^{-1}. The assumption is that the forest stand will approach a maximum sustainable standing stock of 160 MgC ha^{-1} and then take up no additional carbon.

Fig. 9 has been created by simply subtracting the surface in Fig. 7 from the surface in Fig. 8. This new diagram thus represents the net difference between the two scenarios, the net benefit of forest harvest when compared with forest protection (protection against both harvest and natural disturbances such as fire or insect infestation). The amount of carbon sequestered in Fig. 7 could also be seen as an opportunity cost for the harvest scenario in Fig. 8, a C uptake that cannot be realized because of the harvest activity. The result of considering such opportunity cost is that the values for minimum growth rate at which harvest of a forest stand yields net C sequestration becomes larger. Only with growth rates greater than 1.5 to 3 MgC ha^{-1} yr^{-1} (depending on the time consideration) is it possible to sequester more C with forest harvest than with forest protection within a time frame of 20 to 70 years.

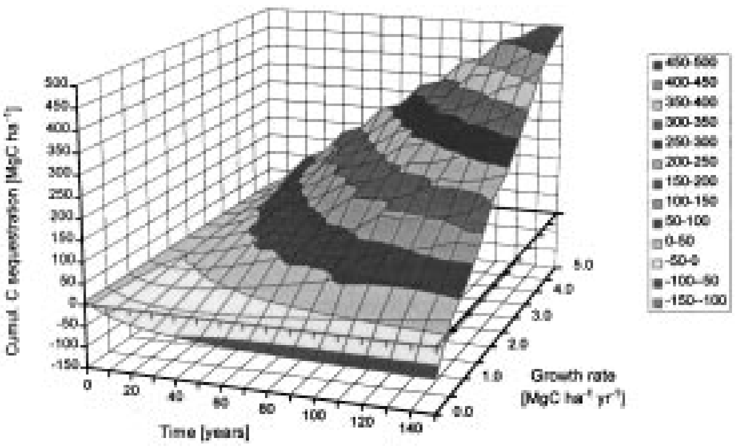

Fig. 8. Harvest of an initial standing stock of 100 MgC ha^{-1} for wood products and biofuels with subsequent regrowth and harvest each time the standing stock reaches 100 MgC ha^{-1}.

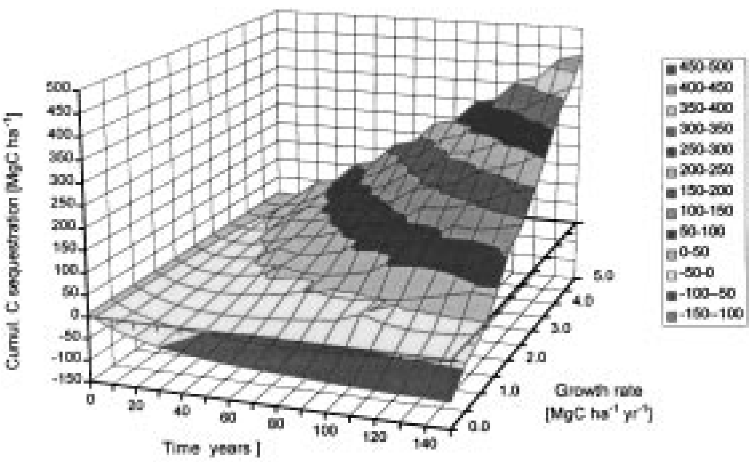

Fig. 9. The net carbon benefit of harvest and use of wood products as opposed to forest protection, as a function of forest growth rate (calculated as the difference between the surfaces in Figs. 7 and 8).

4.3. Discounting the future

The model calculations so far have treated all carbon emissions identically regardless of when they occur. The conclusions can be quite different if we feel that there is a difference in the value of current versus future emissions or emission reductions (Marland et al., 1997; Bird, 1997). Fig. 10 is based on the same model input parameters as is Fig. 3. The difference is that in Fig. 10 carbon flows are discounted at 4% yr^{-1}. The numbers on the contoured surface should now be interpreted as net present value of C flows between time 0 and time *t*, with *t* being as indicated on the front axis of the diagram. Admittedly, it is incomplete to consider the path of net carbon emissions without considering the costs and benefits of these emissions, but the discounted (present value) of C reduction paths may be informative if it indicates cases where net emissions in the near future are barely compensated by net emissions reductions in the distant future.

The main consequence of discounting is that any C fluxes far in the future, either C uptake or C release, do not have a significant impact on the net present value. When very densely stocked

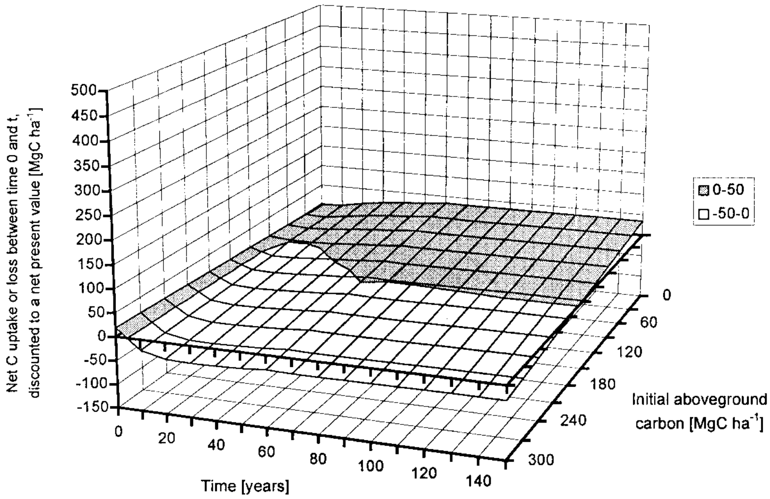

Fig. 10. As Fig. 3, but an annual discount rate of 4% is used to derive the net present value of future carbon flows.

forests are harvested at time 0, the regrowth will require a long time and at least part of this regrowth will be heavily reduced in its impact on the net present value due to discounting. Thus, there is no gain at all in terms of net present value of C to harvest forests with an initial C storage greater than about 150 MgC ha^{-1}.

5. Conclusions

The sensitivity analyses conducted as part of this study show clearly that when forest stands are clear-cut harvested, replaced with fast growing forest stands, and the harvested material is used efficiently to displace fossil fuels, benefits in terms of net emission reductions of carbon to the atmosphere as carbon dioxide are achievable. Not only does the rapidly re-growing stand return carbon from the atmosphere to the biosphere, but the use of biomass products can displace large amounts of fossil fuel use. Nonetheless, it is apparent that for broad ranges of growth rate and product-use efficiency these criteria are not fulfilled and harvest and use of forest products will result in net emissions of carbon for very long times, even when full credit is given for the carbon stored in harvested products and the fossil-fuel emissions avoided. Especially when the cycle of producing forest products includes initial harvest of a forest with a large standing stock of biomass, there is likely to be a long-standing debit in terms of net carbon emissions to the atmosphere.

We have used the GORCAM model with realistic, yet relatively optimistic, values for many parameters related to the efficiency with which forest products are produced, used, and recycled. This allows us to identify some thresholds and to tentatively describe circumstances under which forest harvest is likely to lead to a net increase in atmospheric carbon dioxide that will last on the scale of a couple of decades to a century. If those parameter values related to efficiency were in fact somewhat lower than assumed in our modelling, net C releases to the atmosphere would endure for longer times.

When forest harvest is used efficiently and forest regrowth is rapid with respect to the rate of oxidation of forest slash and forest products, the net carbon balance can be continuously positive following a harvest. Nonetheless, the larger the standing stock of C in above-ground harvestable biomass, the greater the likelihood that clear-cut harvest will result in net emissions of C to the atmosphere and the longer the time required to recover this net debit.

While the exact number depends on the details, when the efficiency of product use falls below some threshold value, recovery to the pre-harvest C balance can take a century or more, or perhaps never occur. Fig. 6 suggests the pre-harvest C balance will never be reached when the “efficiency factor" is below about 1/2 of the value used in our base case scenarios. Further, when the efficiency of product production and use falls below this threshold, increased values for the rate of stand regrowth do not improve the net C balance over time. The qualitative conclusion is straightforward: there is no C benefit from the harvest of forest for forest products unless there is efficient conversion to durable products and/or displacement of fossil fuel use. And, even with efficient product use, a re-growth rate of 0.8 MgC ha^{-1} yr^{-1} (Fig. 4) is required to gain a positive net C balance within 100 years (given the other parameter values chosen here). Any intent to use forest harvesting to help mitigate the buildup of carbon dioxide in the earth's atmosphere will have to demonstrate that the forest regrowth and product use can compensate for any loss from the forest stand as a result of the initial harvest.

When forest products are to be produced from a forest stand that is still growing, any carbon benefit of harvest must be weighed against the opportunity of protecting the forest to accumulate and store additional carbon. This opportunity cost makes for more stringent demands on efficient use of the harvest and the rate of forest regrowth in order to obtain net carbon benefits. In our example, it now requires a rate of regrowth exceeding 1.5 Mg C ha^{-1} yr^{-1} in order to have a net carbon benefit within 100 years of initial harvest.

If there is a discounting of future carbon fluxes, regrowth of the trees will compensate for harvesting of current stands only if the harvest is used very efficiently, the initial stand is storing little carbon, and regrowth takes place quickly enough. It may also be appropriate to discount future C flows because of their uncertainty, uncertainty that arises, for example, from possible climatic changes and their impact on forests, and from changes in political or socio-economic circumstances.

Application of the conclusions drawn here to a specific forest should, of course, consider the magnitude, frequency and control of natural disturbances, factors that will be explored in continuing development of GORCAM. For example, Price et al. (1996) suggest that for the Foothills Forest (located in west central Alberta) "replacing natural disturbances (with a return interval of about 50 years) by sustained yield harvesting (practised on an approximate 80-year rotation) would result in significant increases in total C storage, perhaps exceeding 50% within 150 years, compared to the unmanaged forest, particularly if silvicultural treatments can succeed in maintaining elevated productivity". Inclusion of natural disturbances in our modelling would tend to reduce the "carbon-pay-back-period" of clear-cut harvest.

We return to the question posed in our opening paragraph. Restoration of the net carbon balance to its initial value (with respect to the atmosphere) will be much sooner after a forest harvest if the carbon storage and emissions offset of forest products are included. But even the full system considerations suggest that harvest of mature stands cannot be justified, on carbon considerations, unless forests products are produced and used with considerable efficiency and the rate of anticipated re-growth is high.

6. Acknowledgments

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