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FORESTS FOR CARBON SEQUESTRATION OR FOSSIL FUEL SUBSTITUTION? A SENSITIVITY ANALYSIS

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Abstract—Among the proposals for mitigating the increase of atmospheric CO_2 are the possibility of reforesting degraded lands to sequester C or of using sustainable forest harvests to displace fossil fuels. Storing C on-site in forests and harvesting forests for a sustainable flow of forest products are not necessarily conflicting options if we recognize that their relative merits in mitigating net emissions of C will depend on site-specific factors, such as forest productivity and the efficiency with which harvested material is used. Since the land available for reforestation or development of forest plantations is limited, the relative merits of the different mitigation strategies need to be considered. We use a mathematical model of C stocks and flows to compare the net effect on C emissions to the atmosphere for the two approaches over a range of values of forest productivity and the efficiency of product use. When sustainably-produced forest products are used inefficiently to displace fossil fuels, the greater C benefit is achieved through reforestation and protection of standing forests, and increasing the rate of stand growth yields little gain. However, when forest products are used efficiently to displace fossil fuels, sustainable harvest produces the greater net C benefits, and the benefit increases rapidly with increasing productivity. © 1998 Elsevier Science Ltd

Keywords—Carbon sequestration; afforestation; bioenergy; forests; growth rate; efficiency

1. INTRODUCTION

With the atmospheric concentration of CO_2 increasing, there is evolving an extensive international literature concerned with understanding the balance of C pools and fluxes in forests and forest products.[1–6]

One possibility for mitigating the accumulation of CO_2 in the atmosphere is the collection and storage of C in growing trees, i.e. reforestation or afforestation. Another possibility is the displacement of fossil-fuel combustion through the use of renewable biomass fuels, i.e. by recycling C through biomass fuels. Several authors have discussed the tradeoffs between these two strategies when the amount of land potentially available for growing trees is limited.[7,8] It is also noted that durable wood products provide some storage of C and that all biomass products displace alternate products and services that have different levels of embodied energy.[9–13] The critical elements are that solar energy and the photosynthetic process provide a feasible route to remove CO_2 from the atmosphere, collection of solar energy for this purpose relies on a large area of collectors, and there are options on how the C can be most advantageously stored or recycled once collected.

The success of any mitigation strategy based on forest or land management will depend on a number of variables. Some of these variables will be defined by the physical environment (e.g. climate and land productivity), some can be manipulated as part of a mitigation project and some are imposed on a project by the economy in which it operates (see, for example, Swisher[14]). The challenge for those who would attempt to mitigate net emissions of C to the atmosphere is to have sufficient understanding of the full system of C impacts to be able to take maximum advantage of the opportunities available.

Marland and Schlamadinger[15,16] have used a simple mathematical model (GORCAM) to illustrate the implications for carbon flows of a variety of forest and land management alternatives. Examination of a number of scenarios confirms that while many strategies can result in a net removal of C from the atmosphere, the magnitude of the impact on C flows, and likely the choice among alternative management strategies, depends strongly on a number of site-specific parameters. If we intend to use forest or land management strategies to help mitigate the increasing atmospheric concentration of CO_2, we need to consider these site-specific parameters and determine which is the most appropriate management strategy for a given land parcel. In this analysis we describe two scenarios for management of a particular land parcel, estimate the difference in net reduction of C emissions to the atmosphere for the two alternatives, and then explore the sensitivity of this difference to some of the important parameters in the model. While appreciating that many considerations influence decisions on how land is used, we recognize that there is increasing interest in using forest management to mitigate CO_2 emissions to the atmosphere, and this paper focuses exclusively on C stocks and flows.

2. THE MODEL

The GORCAM model[16] (Graz/Oak Ridge Carbon Accounting Model) describes the changes in C stocks over time for various prescribed land management scenarios. It calculates C accumulation in plants, soils, long- and short-lived wood products, fossil fuels not burned because biofuels are used instead and 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: (1) the allocation of forest harvest to various product and waste streams; (2) the mean lifetime of wood products and of soil and litter C; (3) the efficiency with which wood products are used (and comparable values for the materials they displace); (4) and the energy required for management of the forest products 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.

We compare two forestry scenarios that have been proposed for mitigation of CO_2 emissions. It is assumed that unused or degraded land is available for a forest plantation. The two alternatives considered are: (1) afforestation with the expectation that trees will be protected and allowed to grow and store C away from the atmosphere indefinitely and; (2) development of a short-rotation energy crop with the expectation that the crop will be harvested on a regular basis and used in the place of a fossil fuel. Although we refer to a tree crop, the energy crop could be a perennial herbaceous crop with appropriately chosen rotation time and fuel usage.[17] We focus on two parameters in particular to illustrate the role of the parameters of the site and of the economic/technical setting in which the harvest is used: (1) the growth rate of harvestable biomass (in MgC ha^{-1} y^{-1}); and (2) the efficiency with which renewable biomass C is able to avoid the combustion of fossil fuel C (in MgC of avoided fossil fuel per MgC^{-1} embodied in wood fuel). The carbon content of dry wood is taken to be 50%.

The version of the model employed here uses a simple growth function for trees. It assumes that the landscape will accommodate a maximum stand density of 160 MgC ha^{-1} in above-ground harvestable biomass and that the growth pattern is such that C accumulation is linear with time until half of the maximum is achieved and then slows gradually to approach the maximum asymptotically.[8] The growth rate shown in diagrams below is the rate of C uptake during the early, linear phase of tree growth. In the base case scenario we use a growth rate of 1.72 MgC ha^{-1} y^{-1}, a rate that is appropriate for productive forests in the southeastern U.S.A. or central Europe and yields 100 MgC ha^{-1} after 60 y. In the energy plantation described in the base case, the trees are harvested in a short rotation and the full harvest is used for power generation. Of the harvestable biomass, 20% is lost during harvest and haul and is assumed to oxidize during the year of harvest. C accumulation in soil and litter is calculated with a dynamic model of five litter pools and 1 soil pool.[18]

In the base case scenario we assume that harvested wood is used to displace coal in electric power generation and that 1 kg of C in wood displaces 0.6 kg C in coal. This implies that the net plant efficiency (characterized in terms of CO_2 emissions per kWh) for the wood-fired plant is 60% that of the coal-fired plant it displaces, a value that seems typical of current practice in the U.S.A.[8] It acknowledges that wood has a somewhat higher C J^{-1} value than does coal and that factors like fuel moisture and plant size generally result in lower net conversion efficiency. This displacement factor will be lower if wood is used to displace a less C intensive fuel like oil or natural gas or is used with even lower efficiency; and the displacement factor will be higher if technological improvements can increase the conversion efficiency for wood or if wood is used in combined heat and power (CHP) plants to displace separate heat and power facilities, etc. The upstream costs of fuel harvest or mining, fuel preparation and transport, etc., both for the biofuel and for the fossil fuel for which is it substitutes, are not included in the displacement factor but are represented separately in our model. Our base case scenario describes an optimal situation where wood is harvested mechanically, hauled only a short distance and used to displace coal for power generation. In this case the resource requirements for harvest, haul and fuel preparation of the wood are approximately the same as for mining and delivery of coal,[16] and these cancel out and are not represented in the figures below. If the forest was such that harvest was more complex or less efficient or the haul distance longer, the model would show a net greenhouse gas debit against the fuel displacement scenario and the afforestation scenario would be relatively more attractive. In general, factors that negatively impact the economics will negatively impact the net C benefit as well.

3. ANALYSIS

Figure 1(a) illustrates model output for the cumulative changes in C stocks in the various pools on 1 ha of land for the afforestation scenario. C accumulates in the soil and litter and the trees grow at a linear rate for $160/2/1.72 = 46$ y, where 1.72 is the specified growth rate in MgC ha^{-1} y^{-1}. Figure 1(b) illustrates the comparable changes in C stocks for a biomass energy plantation. Figure 1(b) is based on the unlikely circumstance that productivity is the same for both scenarios. A more likely circumstance is that selection of optimal species and intensive management would result in higher yields in short-rotation plantations than on afforested land, and the importance of this is illustrated below. Whereas 1.72 MgC ha^{-1} y^{-1} may be an appropriate growth rate for an afforestation project, it is likely that multiples of this growth rate will be necessary to produce an economically viable short-rotation energy plantation and are achievable.[17,19] So long as the growth rate is the same for both scenarios, the net C benefit at the end of 100 y will be greater for the afforestation scenario because the periodic harvests of fuel avoid emission of only 0.6 units of fossil fuel C for each unit of biomass C burned. At 100 y the afforestation scenario shown is beginning to be saturated with C as the trees approach the maximum sustainable on-site biomass, and if the scenarios were carried out for some additional 50 y the net C savings would then be approximately equal for the two scenarios and subsequently greater for the biomass fuel scenario.

As noted above, the amount of C sequestered over time is sensitive to the multitude of parameters that determine the tree growth rate. For the energy plantation scenario, the net C benefit is also strongly dependent on the multitude of parameters that ultimately define the displacement efficiency of biofuels. Figure 2 shows the net C benefit of our two scenarios at the end of 40 y as a function of the growth rate and displacement factor (MgC of avoided fossil fuel/MgC embodied in wood fuel). In Fig. 2(a), for the afforestation scenario, there is no harvest and hence the net C accumulation depends only on the growth rate. It is easily observed that the total C accumulated at the end of 40 y increases with growth rate, but that the increase is less than linear with time (as in the cross section represented by Fig. 1(a)) because of C saturation prescribed at 160 MgC ha^{-1}. In Fig. 2(b), for the energy plantation, the net C benefit increases with both growth rate and displacement factor. In this energy plantation scenario there is no C saturation phenomenon and the net C benefit can be very high when biomass grows rapidly and is used efficiently. In the range of scenarios represented by Fig. 2(b) we have taken the harvest-cycle time to be a function of the biomass growth rate. In particular, the harvest-cycle time is assumed to be such that the amount of biomass harvested is always 50 MgC ha^{-1}, i.e. for the basic growth rate in Fig. 1(b) the rotation period is about 30 y. For a doubled growth rate the rotation period is 15 y and so on.

Figure 3 shows the difference after 40 y when the results for the afforestation scenario are subtracted from the comparable values for the energy plantation scenario. Positive values indicate that the energy plantation provides greater net removal of C from the atmosphere for the set of values of growth rate and displacement factor, while negative values indicate that greater C benefit is provided with the afforestation scenario. The inset to Fig. 3 provides a two-dimensional contour plot of the same information in order to make the shape and location of the zero contour more clear. Figure 3 suggests that, with equal growth rates for afforestation and plantation forestry, very high growth rates (6.5 MgC ha^{-1} y^{-1}) are required before higher net C benefits are provided within 40 y by an energy crop plantation (at 0.6 displacement factor). It is to be expected, however, as already noted, that intensive management of short rotation plantations would yield higher growth rates than available in an afforestation project. Figure 4 is identical to Fig. 3, except we have assumed that intensive management yields twice the productivity on the energy plantation as when the

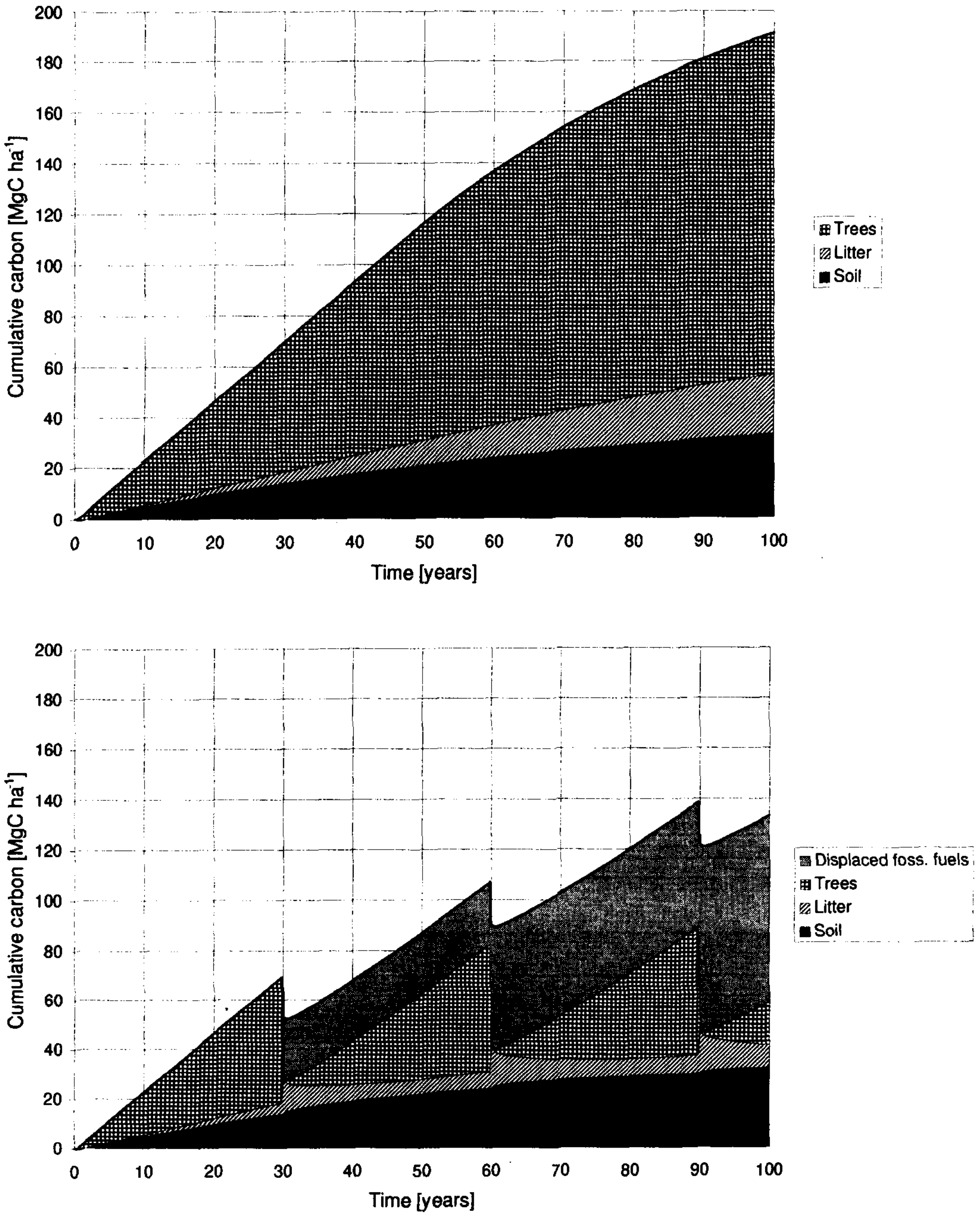

Fig. 1. Carbon sequestration in soil, litter and trees for an afforestation project (a, top) and in soil, litter, trees and displaced fossil fuels or a forest plantation harvested for fuelwood (b, bottom).

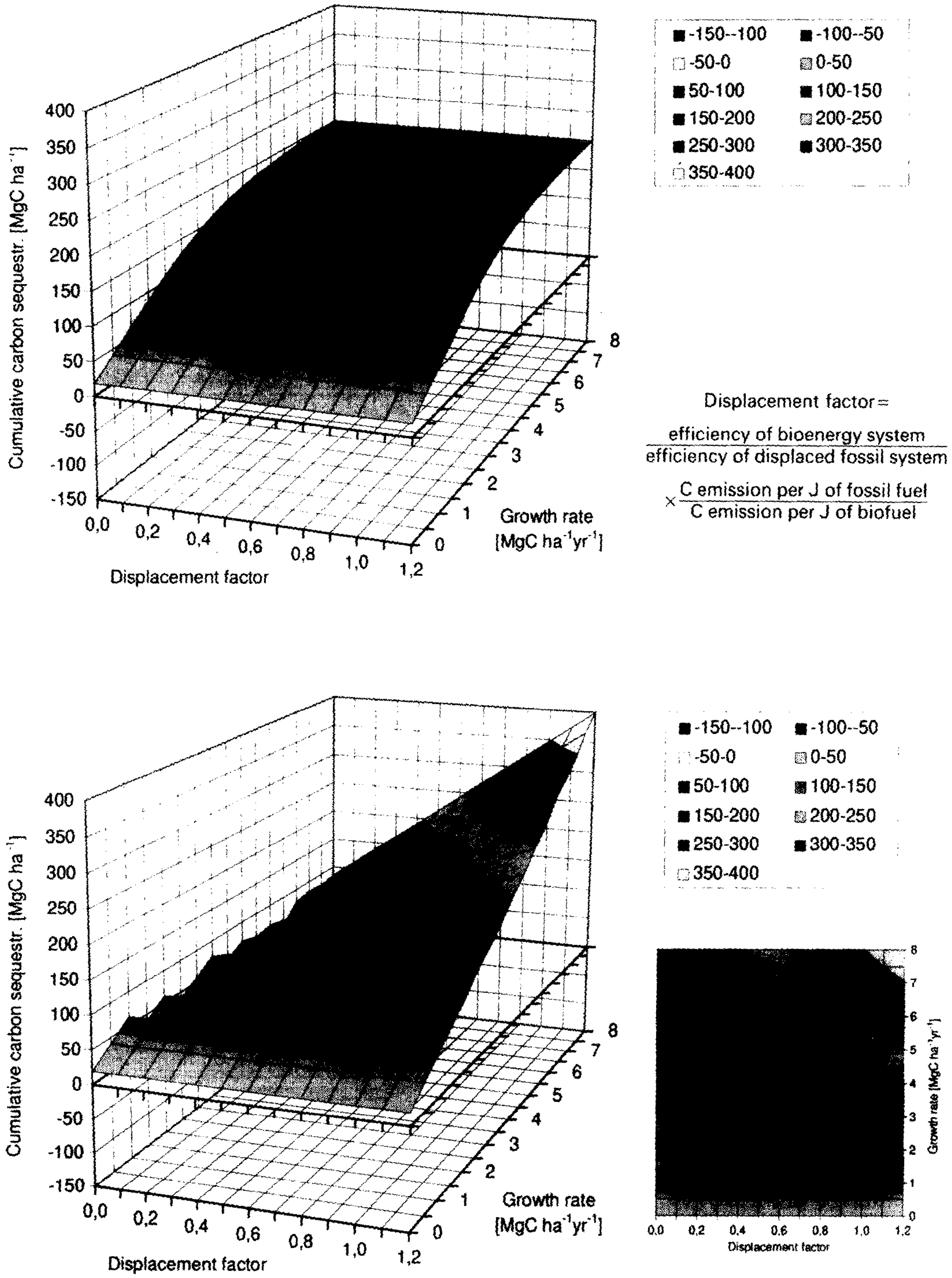

Fig. 2. Cumulative C sequestration after 40 y for afforestation (a, top) and a fuelwood plantation (b, bottom) as a function of the growth rate and the efficiency of fossil fuel substitution (displacement factor).

site is afforested. (The labels on the growth rate axis in Fig. 4 now apply to only the energy plantation scenario.) It is seen that an energy plantation with 0.6 displacement factor can yield more net savings in C emissions than afforestation if intensive management can increase productivity from 1 MgC ha^{-1} y^{-1} in an afforestation project to 2 MgC ha^{-1} y^{-1} in the energy plantation. It still requires very high productivity if the biomass fuel is used to displace oil or natural gas (the displacement factor drops to 0.50–0.55 if wood is used to displace residual fuel oil rather than coal for power generation). If biofuel can be used with

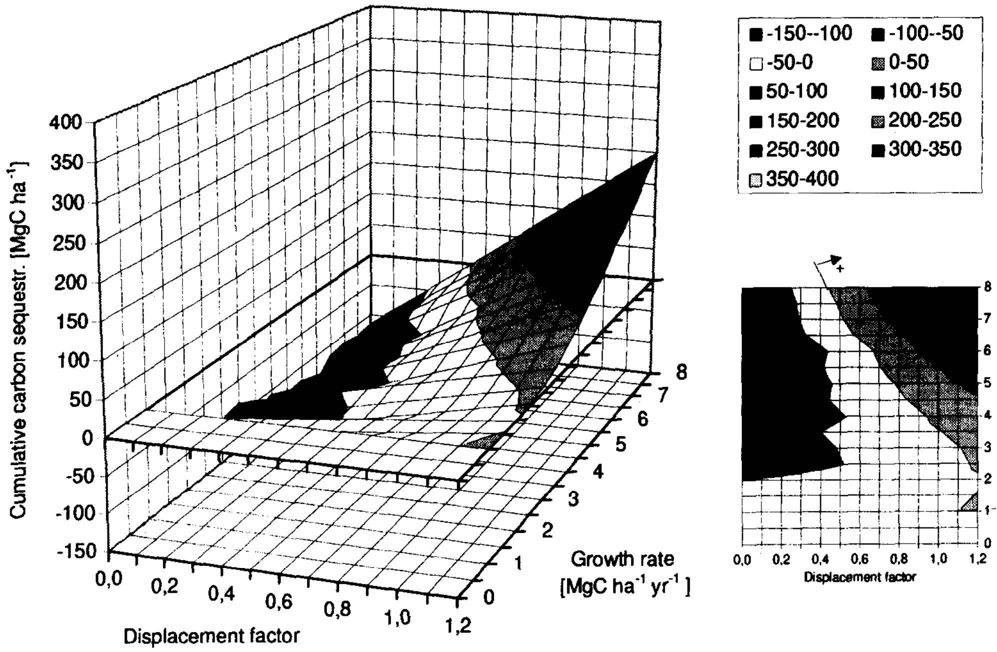

Fig. 3. The difference after 40 y between the two diagrams in Fig. 2. Positive values indicate that fuelwood harvest is the better choice.

the same net efficiency as displaced coal (displacement factor = 1), it becomes the better choice for mitigation even at very low values of productivity. Figure 5 shows that the C benefit of the biofuels scenario is greater over a large portion of the growth rate/displacement factor

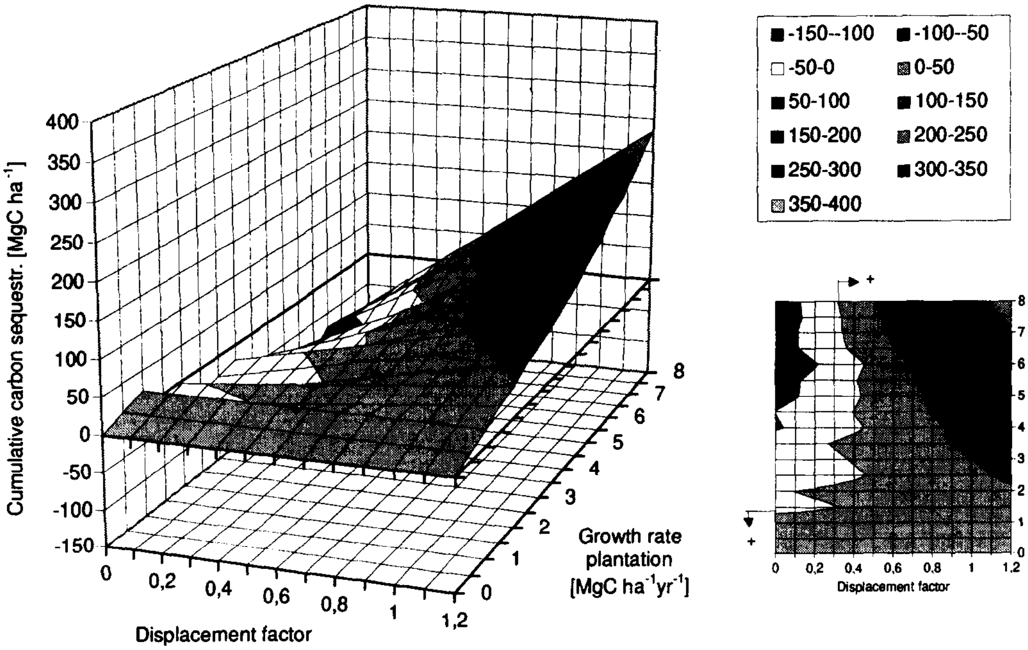

Fig. 4. As in Fig. 3, but here the difference after 40 y is calculated in a way that the growth rate in the plantation is taken to be twice the growth rate for afforestation without harvest. Positive values indicate that fuelwood harvest is the better choice. Here it is important to note that for growth rates smaller or equal 1 MgC ha^{-1} y^{-1} no harvest takes place in either of the scenarios, because in the plantation 50 MgC ha^{-1} are never reached, so that: (1) carbon sequestration values do not change in the figure for changing displacement factor; and (2) the small C uptake shown is due to a slightly better C balance of soils and litter in the plantation (due to the doubled growth rate).

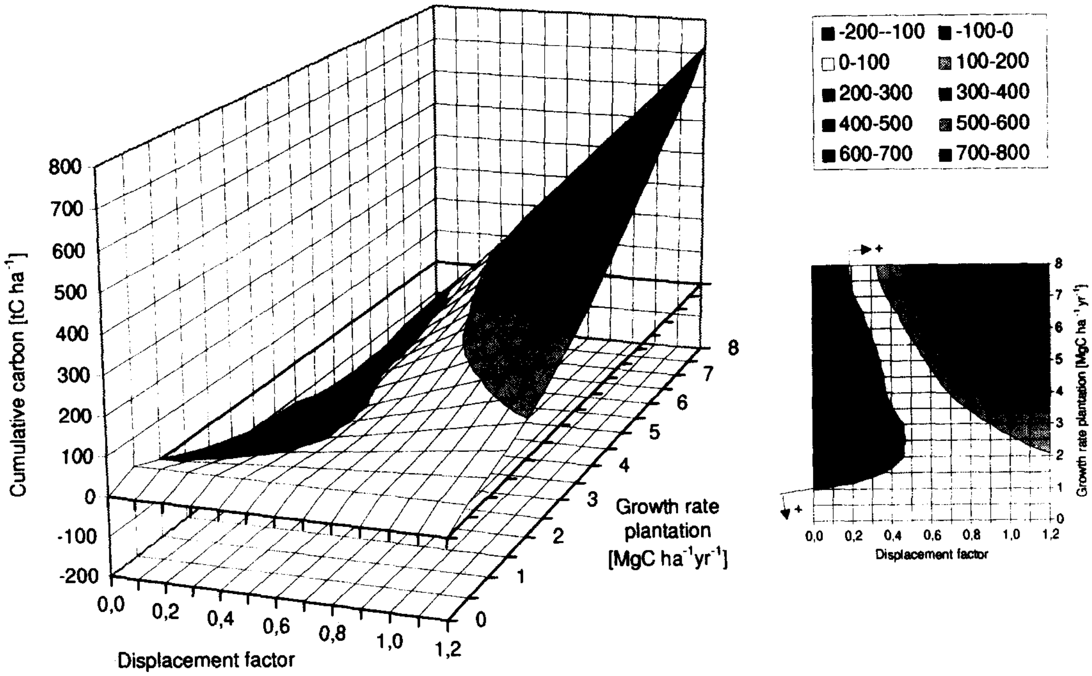

Fig. 5. As in Fig. 4, but after 100 y instead of 40 y.

field after 100 y. In Fig. 5, as in Fig. 4, the growth rate for the fuelwood plantation is taken to be twice that for afforestation. The net C benefit can be very large, especially when high productivity is possible. In the high productivity case, saturation occurs early in the afforestation scenario, while the energy plantation continues to provide C emissions offsets. If the maximum stand density was larger or was taken to depend on stand productivity, the curvature of the net carbon plane in Fig. 2(a) would be less and the sequestration scenario would be relatively more attractive over a larger range of growth rates and time intervals.

4. DISCUSSION

Schlamadinger and Marland[16] and others, have described the relative benefits with respect to the net impact on CO_2 emissions to the atmosphere of using land to grow woody crops as opposed to simply afforesting the land with the intent of storing C in standing trees. In many cases there are significant C benefits to be gained from substitution of forest products for alternate sources of energy or for alternate products or services that require considerable energy for their production. None the less, these C benefits generally require high growth rates, high efficiency of product harvest and use and/or long accounting times. We need to be able to recognize and appreciate circumstances where this approach provides the greater C benefit as opposed to afforestation and forest protection and where the payback times are very long.[1,20] We also need to understand the potential rewards from improvements in forest productivity or in combustion efficiency, etc.

The sensitivity analysis summarized in Figs 3 – 5 shows that net C sequestration potential is very sensitive to the efficiency with which forest products substitute for alternate fuels or products. We have taken a base case with the fossil fuel displacement factor equal to 0.6, but in real world applications this factor might range from essentially zero to approaching 1.5. The value would be near zero if additional biomass energy supply leads to increased energy consumption without displacing fossil fuel, and it could approach 1.5 if separate inefficient sources of fossil heat and power are displaced with a biomass cogeneration plant.

The possibility of avoiding net emissions of C to the atmosphere is also very sensitive to the forest growth rate and there is a wide range in the potential values for forest growth rate. Values of C uptake in productive forests, including soil and litter, might range from 0.8 to over 5 MgC ha^{-1} y^{-1} (Nabuurs and Mohren[12] for selected forest types at moderate production levels). Nilsson and Schopfhauser[21] estimated that a total of 345 × 10^6 ha of land could be available globally to sequester C at a maximum rate of 1.14 PgC y^{-1} in aboveground biomass for 60 y; an average of 3.3 MgC ha^{-1} y^{-1}. Maclaren[22] reported a total biomass C storage in radiata pine plantations of 231 MgC ha^{-1} for 30 y, of which 50% is in harvestable stemwood. Wright and Hughes[23] reported a mean biomass yield of 4–10 MgC ha^{-1} y^{-1} for experimental plots of short-rotation woody crops in the north-central region of the U.S.A. NOVEM[24] concluded that with short-rotation poplar a yield of 7.5 MgC ha^{-1} y^{-1} seems realistic for the year 2000 for the middle and south of the Netherlands provided enough water and minerals are being supplied. Also, there are large areas of forest where low temperatures, inadequate rainfall, poor soils, etc. result in growth rates less than 0.8 MgC ha^{-1} y^{-1}.[25,26]

The calculations in this paper have shown that there are tradeoffs between maximized C storage and maximized fossil fuel substitution (see also, for example, Cooper[27]). In cases with intensive management and harvest, the mean on-site C storage may be significantly lower than for afforestation with the aim of storing C. However, the total impact on C emissions to the atmosphere can be greater, depending on factors such as forest growth rate and the efficiency of product use. We have not yet explored alternatives like selective logging, where forest is used to supply harvestable biomass without compromising all of the C accumulation in an afforestation project.

The model results also reveal that the C benefits of forest products scenarios are much enhanced if forest productivity is increased, perhaps by selection of appropriate species or through improved management practices. However, when the displacement factor is low, i.e. harvested wood is used with low efficiency, there is no advantage to higher growth rates. Figure 4 shows that for values of the displacement factor lower than about 0.4, the C benefit of fossil-fuel substitution is very low regardless of the forest productivity. On the other hand, once the displacement factor rises above some threshold value, the magnitude of net C benefits increases very rapidly as the growth rate increases. This suggests that the highest priority for improving net C benefits from forest management is to insure that forest products are harvested and used efficiently. Improvements in productivity will then enhance benefits further.

It is clear that there is not a one-size-fits-all strategy for optimal management of all land available for forest management to mitigate CO_2 emissions. Results from modelling of this kind can provide some guidance on which directions in research and public policy offer the greatest opportunities for significant improvements. They should also be able to sensitize individual project proposals to the options available and the foci for particular attention. The success of any mitigation project relying on the use of biomass as a fuel will be strongly dependent on site-specific parameters and on the technical factors of energy substitution. Considering that land resources are limited, these parameters play a key role in determining whether fossil fuel substitution should be preferred to on-site C sequestration strategies.

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