INCORPORATION OF BIOMASS INTO FOREST SOILS FOR ENHANCED PRODUCTIVITY, RESTORATION AND BIOSTORAGE: A MODELLING STUDY TO EVALUATE RESEARCH NEEDS*

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ABSTRACT

The concept of using multiple rotations of fast-growing fibre/energy plantations for restoring soil capacity was evaluated using the CO2FIX model. The simulation analysis considered portions of such stands being incorporated back into the soil at the end of each rotation and with different product scenarios. The analysis of nine simulated scenarios illustrating a range of mixes of energy, pulp, and solid wood products, as well as incorporation of biomass into the soil and productivity differences, using the model CO2FIX showed: (1) shifting the mix to more durable products significantly increased the amount of carbon sequestered, (2) increases in stand productivity increased carbon sequestration potential, and (3) productivity increases and incorporating biomass into the soil appear to have the biggest payback for carbon management. These simulation results show there may be potential for the use of short-rotation woody crops as a way to mitigate previous long-term soil depletion activities and to increase carbon sequestration. Research needs indicated by this simulation analysis include: (1) appropriate functions for decomposition and transformation of buried biomass for incorporation into carbon management models, (2) incorporation of feedback mechanisms into carbon management models reflecting the impact of soil and management changes on productivity, and (3) a means of crediting carbon as offsets to fossil fuel in a closed-loop biofuel cycle.

Keywords: biomass incorporation; biostorage; mulching; CO2FIX; simulation study.

INTRODUCTION

Many forest sites are depleted and have limited amounts of soil organic matter, nutrient pools, and carbon capacity. Over many rotations, forest operations contribute to site impacts by changing soil structure and removing above- and below-ground woody biomass. A possible way of enhancing soil productivity and restoring depleted sites is through the incorporation of organic material (indigenous woody residues and/or other acquired organic material such as city and mill wastes). Also, the incorporation of such materials may go beyond the re-building of soil capacities; it may be a way of using the soil for bio-storage of

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carbon-laden materials as part of a sequestration effort to reduce global warming. Little is understood about the effects of incorporating carbon on soil carbon form, carbon retention, and ultimately nutrient cycles as a way to mitigate forest site impacts. Some research has focused on the application of organic material on to soils, and the biological and environmental effects of such efforts.

Short-rotation woody crops (SRWC) offer many opportunities for fibre and biofuel production as well as economic and environmental benefits. Pulp and chemicals from these intensively managed crops can replace those derived from hardwood imports. Properly implemented, woody crops can reduce seasonal and weather-induced fibre supply shortages and they offer potential for local supplies near conversion facilities, reducing transportation energy and costs. By increasing output per unit area on marginal lands that might otherwise be unproductive, SRWC can displace procurement from, and thereby conserve, sensitive forest sites. Farm-raised trees can also serve as a renewable alternative to fossil fuels, helping to meet increasing demands for an environmentally acceptable domestic energy source, generating jobs, and improving local economies. In addition to environmental benefits discussed by Tolbert & Schiller (1996), SRWC systems have the potential for increasing soil carbon through root and litter additions (Mehdi *et al.* 1999).

A potentially effective means of increasing and stabilising soil organic matter is through the application of organic soil amendments, and forest biomass in the form of logging residues is usually a readily available source. Potential benefits of biomass incorporation include: (1) good site preparation provided by comminuting slash and stumps, (2) improved nutrient retention and carbon pools, (3) potential for slowed wood decomposition, reduced carbon dioxide flux, and increased carbon storage times, (4) carbon more readily available for nutrient cycling and retention, and (5) improved soil physical properties that enhance both short- and long-term productivity. Coupled with the need for site preparation treatments that include stump and slash clearing or displacement from the planting row, biomass and slash mulching and incorporation into the soil have potential as a means to accomplish all these objectives (Buford *et al.* 1999).

There are no data available from which to determine the benefits of incorporation or to determine how much of the biomass in a given stand might best be used for incorporation. There are many studies that examine bedding as a forest practice and subsequent forest growth (Tiarks & Haywood 1996; Carter *et al.* 1998; Gent *et al.* 1983; DeWit & Terry 1982). However, studies that examine the impact of biomass incorporation on the relationship between productivity, carbon sequestration, and soil processes are few and recent, and so results are very preliminary (Sanchez *et al.* 2000). Extremely limited data mean that potential trade-offs in using biomass for energy, for fibre and solid wood products, and for incorporating into the soil have not been quantified. We can begin to consider these potential trade-offs using models to predict cumulative outcomes; however, models that operate at the stand level, consider the above- and below-ground components of the stand and the soil, account for the products from the stands, and accumulate the carbon sequestered over multiple rotations are not well developed.

We used the model CO2FIX to simulate the carbon sequestered across five rotations of hybrid poplar grown in the southern United States under a short-rotation woody cropping system. A complete description of the model and its assumptions have been presented by Mohren & Klein Goldewijk (1990) and Mohren *et al.* (1999). This model has the primary components needed for this analysis and has been used to compare carbon sequestration patterns from a variety of stand types (Nabuurs & Mohren 1995). To the extent possible with such a simulation model, the functions and cumulative results from the model have been validated using existing data sources and other studies as described by Mohren & Klein Goldewijk (1990) and Nabuurs & Mohren (1993). No other readily available models provided the cumulative analysis and output described above. Simulated results from a number of scenarios reflecting mixes of energy, pulp, and solid wood products, as well as incorporation of biomass into the soil, are illustrated and compared.

METHODS

For this analysis, we used hybrid poplar grown in the south-eastern United States. CO2FIX operates from yield information provided by the user but there were no readily available yield tables or functions for hybrid poplar in the south-eastern United States, and so we estimated yields by developing a function for predicting yield from age using the information on eastern cottonwood (*Populus deltoides* Bartr.) and average conditions reported by Cao & Durand (1991). We scaled this function by using the regional yield information reported by Walsh & Becker (1996). Predicted yields compared favorably with those reported by Strong & Hansen (1993) and were subsequently used in the model analysis. Total carbon accumulated (above-ground biomass, soil, and products) was modelled over five consecutive 12-year rotations and compared at the end of the 60-year period.

Variables required for this analysis were rotation length and number of rotations; initial biomass in the foliage, roots, litter, soil humus, branches, stems, and dead wood; harvest age and mix of products; stemwood density and carbon content; mortality; average residence time of carbon in wood products; litter decomposition rate; and yield information. Initial values for these variables were taken from the yield table analysis described above and from the literature (USDA Forest Service 1987; Skog & Nicholson 1998; USDA Natural Resources Conservation Service 1994; Nabuurs & Mohren 1995). The dynamics of the forest soils component are characterised by the decomposition rates of litter and stable humus and humification rates of litter (Mohren *et al.* 1999). Results of model runs for CO2FIX for longer rotation lengths show accumulating soil carbon after initial loss (Nabuurs & Mohren 1995). Over the short rotation length of 12 years used in this simulation study, CO2FIX appears to show decreasing soil carbon. The model assumes that litter and dead wood on the mineral soil and stable humus incorporated in the mineral soil belong to the soil organic matter compartment (Nabuurs & Mohren 1995; Mohren *et al.* 1999). Complete details of the model and component descriptions have been given by Mohren & Klein Goldewijk (1990).

A set of nine scenarios was developed to compare total carbon accumulated over a range of options. These options included a variety of product distributions, incorporating a portion of the above-ground biomass into the soil at the end of each rotation, and increases in productivity projected from genetic, silvicultural, and soil improvements. Initial soil parameters needed were taken from the laboratory and survey description of an Orangeburg soil (fine-loamy, kaolinitic, thermic typic kandiudult) (USDA Natural Resources Conservation Service 1994). This soil series is widely distributed throughout the forested areas of the south-eastern United States. Given the intensive nature of short-rotation woody crop systems that include frequent and closely monitored nutrient additions, no nutrient shortages were assumed. Percentages chosen for each product class were based on current utilisation and market trends. An increase in yield of 10% per rotation was used, based upon historical trends in returns from intensive management (Haynes *et al.* 1995).

The scenarios are listed in Table 1. Product classes were energy, pulp, composite products, and solid wood. The percentages given in Table 1 are percentages of standing volume. The model directs the proportion of stand volume to the product classes, rather than allowing for choice of specific tree or stand components, such as tops and branches, to be apportioned to each use. For Scenarios 7, 8, and 9, the rotations were run individually, rather than as a consecutive batch, to allow altering of the initial values of carbon in the soil and the yield functions for the second and subsequent rotations to account for the incorporation of biomass into the soil and the projected increase in yields. CO2FIX accumulates and reports the carbon in each component (stand, soil, and products) over the five rotations automatically. Since the rotations in Scenarios 7, 8, and 9 were projected individually, the results were manually summed across rotations to provide the same output as for Scenarios 1–6.

TABLE 1–Product distribution and biomass incorporation scenarios.

Scenario	Energy* (%)	Pulp (%)	Composite (%)	Solid wood (%)	Incorporated (%)
1	100	0	0	0	0
2	30	70	0	0	0
3	30	50	0	20	0
4	30	0	70	0	0
5	30	0	50	20	0
6	30	0	0	70	0
7	30	20	0	20	30
8	0	50	0	20	30
9†	30	20	0	20	30

* Percentages are a percentage of the standing above-ground volume.

† Scenario 9 is the same as Scenario 7 with an increase in yield of 10% each rotation to reflect potential genetic, silvicultural, and soil improvements.

RESULTS

An example of the model output showing results for Scenario 1 is given in Fig. 1. Reductions in the carbon in the product pool reflect the use of all harvested biomass for energy which is all emitted to the atmosphere after 2 years. The soil carbon pool increases immediately after each harvest (resulting from the addition of roots of the harvested stand and slash to the pool), but then gradually decreases over each rotation, reflecting the continually decreasing soil carbon pool model.

A comparison of the outcomes for all carbon pools for Scenarios 1, 3, 7, and 9 is shown in Fig. 2. It is clear, as expected, that shifting harvested material into longer-lived products (Scenario 3) increases the amount of carbon sequestered relative to Scenario 1. These simulations suggest that, even under the model of continual soil carbon decreases, incorporating biomass into the soil can raise carbon levels in the soil. There was no feedback mechanism in the model providing for increases in productivity associated with soil organic matter increases, either from incorporation or from root biomass. Scenario 9 has the same product

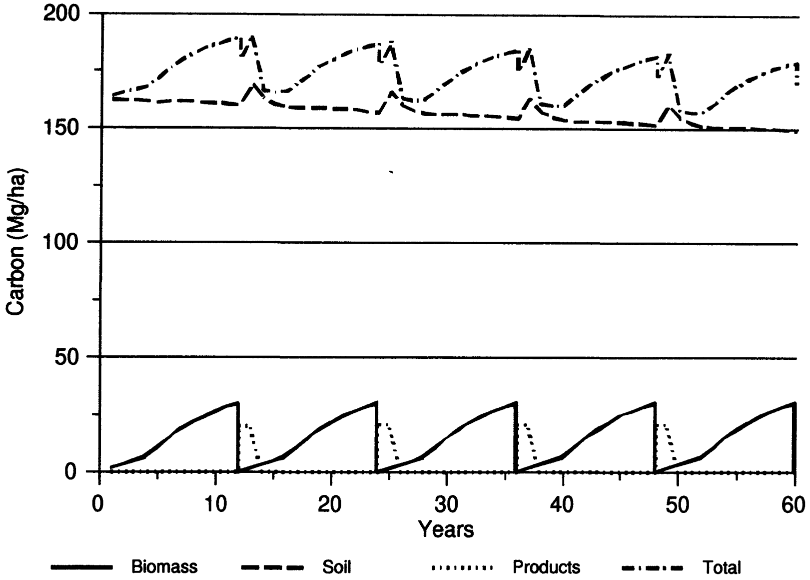

FIG. 1–Model output for Scenario 1 showing carbon accumulated over five 12-year rotations with 100% of the biomass going to energy.

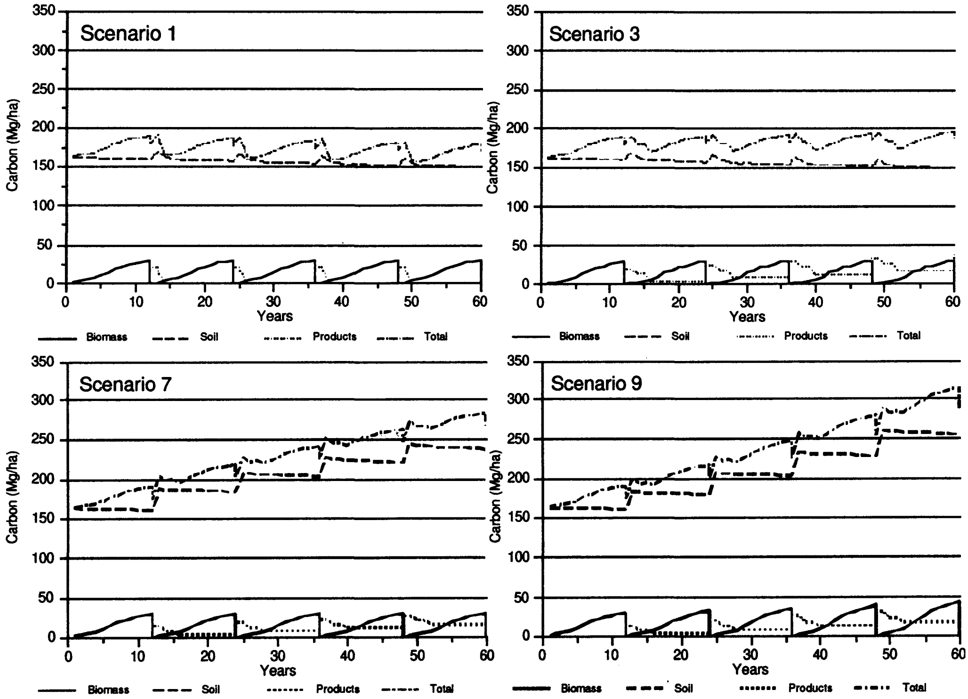

FIG. 2–Comparison of model output for Scenarios 1, 3, 7, and 9, showing carbon accumulated over five 12-year rotations.

mix as Scenario 7 and reflects an assumed productivity increase of 10% per rotation. This adds to both the above- and below-ground pools and is reflected in the trends shown in Fig. 2. A comparison of the total carbon accumulated over the five rotations for all nine scenarios is shown in Fig. 3. Scenarios 6 and 5 show the impact of higher percentages of longer-lived products. Numerical results, in decreasing order, are given in Table 2. The results shown in Fig. 3 and Table 2 do not account for the net-zero offsets of using renewable energy sources, i.e., for carbon that would have been released from equivalent fossil fuels.

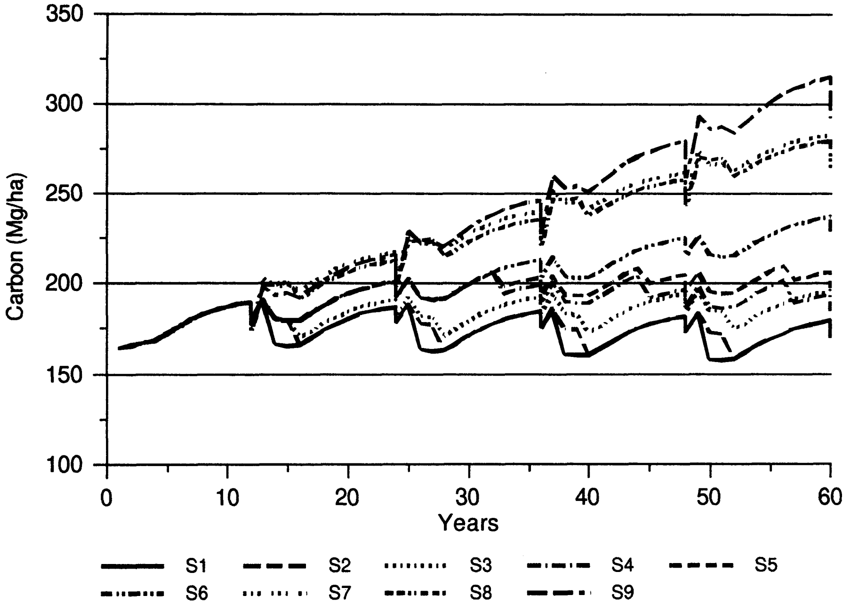

FIG. 3–Comparison of total carbon accumulated for Scenarios 1–9 for five 12-year rotations.

TABLE 2–Total carbon accumulated, in decreasing order, for Scenarios 1–9.

Scenario	Total (Mg/ha)	Biomass (Mg/ha)	Soil (Mg/ha)	Products (Mg/ha)
9	315	43	254	18
7	282	30	237	17
8	279	30	233	17
6	237	30	149	58
5	206	30	149	27
3	196	30	149	17
4	194	30	149	15
2	179	30	149	0
1	179	30	149	0

CONCLUSIONS

The analysis of nine scenarios illustrating a range of mixes of energy, pulp, and solid wood products, as well as incorporation of biomass into the soil and productivity differences using the model, CO2FIX, suggested: (1) shifting the mix to more durable products significantly increases the amount of carbon sequestered, (2) increases in stand productivity increase carbon sequestration potential, and (3) productivity increases and incorporating biomass into the soil appear to have the biggest payback for carbon management. Research needs shown by this analysis include: (1) appropriate functions for decomposition and transformation of buried biomass for incorporation into carbon management models, (2) incorporation of feedback mechanisms into carbon management models reflecting the impact of soil and management changes on productivity, and (3) a means of crediting carbon as offsets to fossil fuel in a closed-loop biofuel cycle.

Accurate knowledge of carbon dynamics at the landscape and stand scale is needed to predict and manage forests for uses which include carbon sequestration and biofuel production. This information is also needed to determine what the highest use of standing biomass might be for a given soil/stand condition. Presently, models that evaluate the potential of different forest management options and product uses for sustainability include a limited amount of information on carbon dynamics.

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