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CARBON STORAGE AND RECYCLING IN SHORT-ROTATION ENERGY CROPS[1]

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Summary

Short-rotation energy crops can play a significant role in storing carbon compared to the agricultural land uses they would displace. However, the benefits from these plantations in avoiding further use of fossil fuel and in taking pressure off of native forests for energy uses provides longer term carbon benefits than the plantation carbon sequestration itself. The fast growth and harvest frequency of plantations tends to limit the amount of above- and below-ground carbon storage in them.

The primary components of plantation carbon sequestering compared to sustained agricultural practices involve above-ground wood, possible increased soil carbon, litter layer formation, and increased root biomass. On the average, short-rotation plantations in total may increase carbon inventories by about 30 to 40 tonnes per hectare over about a 20- to 50-year period when displacing cropland. This is about doubling in storage over cropland and about one-half the storage in human-impacted forests. The sequestration benefit of wood energy crops over cropland would be negated in about 75 to 100 years by the use of fossil fuels to tend the plantations and handle biomass.

Plantation interactions with other land uses and total landscape carbon inventory is important in assessing the relative role plantations play in terrestrial and atmospheric carbon dynamics. It is speculated that plantations, when viewed in this context, could generate a global leveling of net carbon emissions for approximately 10 to 20 years.

KEY WORDS: Carbon, energy crops, sequestration, biomass

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Introduction

Plantations of trees managed for fast growth and as a renewable fuel may provide opportunities to alter net carbon emissions in selected regions around the world. These short-rotation plantations of 2- to 10-year harvest cycles and possible coppice regeneration are defined in contrast to long-rotation plantations, natural forests, and agricultural crops because of their special combination of high productivity, early fast growth, multiyear growth processes, site and management requirements, and overall effects on net carbon dynamics. They can play a significant role in altering agricultural and forest land use as well as fossil fuel utilization which in turn affect net global carbon dynamics.

There are three important considerations in describing the effects of energy plantations on net carbon emission dynamics. These are the average amount of carbon stored over long periods, the type of fuel and conversion processing that plantation wood may displace, and the net change in overall land use generated by biomass utilization for energy.

The intent is to provide an evaluation of the processes affecting potential changes in net carbon emissions to the atmosphere with respect to short-rotation plantations used for energy production. Although the focus is on plantation carbon sequestration, the other aspects of plantations affecting carbon dynamics are included for consideration.

It is recognized that some important factors influencing energy crop carbon balances are not addressed. For example, environmental regulations, policies, and economics governing land use and price supports in agriculture, forestry, and energy are not considered. A preliminary understanding of these factors is only beginning to emerge. Also, the effects of climate change on plantation processes are not addressed.

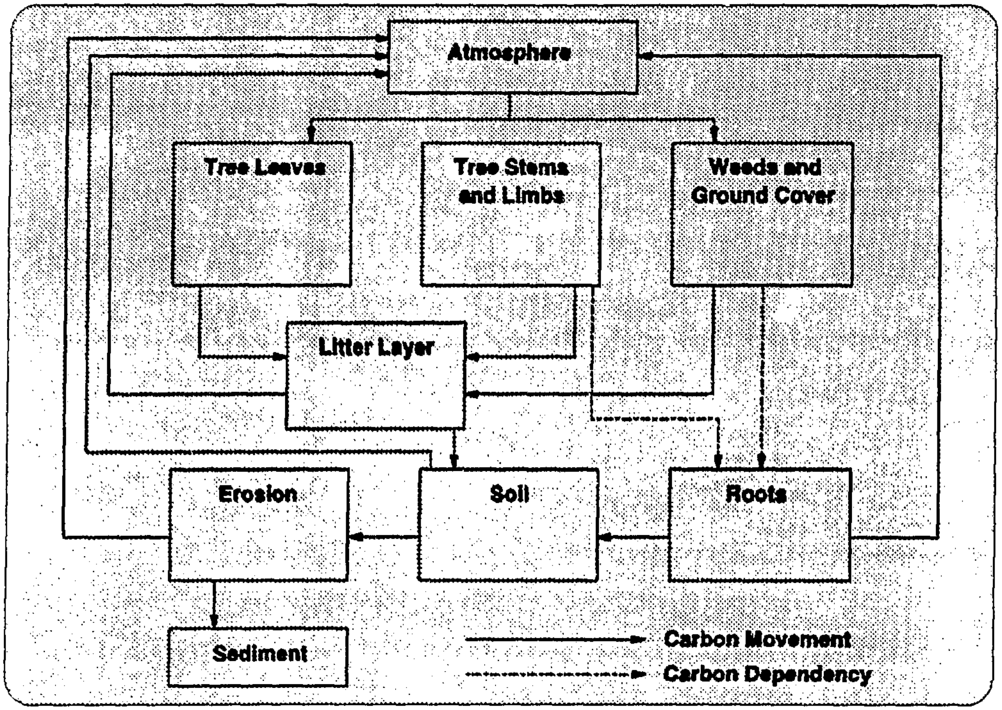
Carbon Storing Processes in Short-Rotation Energy Crops

Processes controlling carbon inventories in plantations are most easily divided into those which act above- and below-ground (figure 1). Above-ground inventory components include tree stems and branches, leaves, and weeds. The below ground inventory components include litter, soil, and roots. The processes which act on these inventory components are many and only the major ones are summarized. For simplicity of discussion, dry biomass and organic matter is considered to be 50% carbon.

Above-Ground Processes

Plant growth, mortality, and removal of trees are the variables driving above-ground sequestration. These variables have a strong relationship with the rest of the plantation carbon components. Energy plantation stem and branch growth has been measured at 10 to over 30 dry tonnes of biomass per hectare per year when measured at rotation age (IUFRO 1984, Gessel 1981, Cannell 1982, Ranney et al 1987). This converts to 5 to 15 tonnes per hectare per year of carbon. Mean world figures for successful long-rotation plantation carbon production are in the 5- to 6-tonne rate range (Cannell 1982). Short-rotation plantations more frequently range in the 6- to 9-tonne carbon per year range (figure 2) although future growth rates may be in the 7 to 10 tonnes C per year range. This is the net carbon accumulated each year as live stems and branches. Figure 2

Figure 1. Above- and Below-ground Carbon Inventories and Pathways Associated with Short-rotation Plantations



but long-tilled agricultural soil placed into energy plantations will be zero to one tonne C per hectare-year and reaching near equilibrium within 30 to 40 years. Experiments in Sweden, however, where organic matter has been added to sites at rates of 10 tons/ha/yr over more than 10 years is only beginning to show increases in soil C. To complicate issues, in the tropics certain grasslands have been found to contain more soil carbon than neighboring forests in the same life zone. Perhaps in part due to the high allocation of grass photosynthate below ground. Also, in the same region forest regeneration after agriculture has nearly doubled soil carbon in a decade. It is not clear either how fast or how much carbon will accumulate in soils but rates appear to slow with increasing latitude.

The bottom line appears to be that changing land use from agricultural crops to energy crops will likely increase soil carbon alone by -5 to +10 tonnes per hectare depending on a wide range of factors. How fast this will happen is unclear but the amount of carbon will depend on soil wetness and temperature. Converting forests to wood energy crops may generally reduce soil carbon inventories by perhaps 5 to 10 tonnes of carbon per hectare in temperate regions but little data are available. The variation in this value is extreme from site to site. Some studies in the tropics indicate that there may be little difference between forests and plantations in soil carbon. However, forests tended to increase soil carbon via fine root growth whereas plantations provided carbon inputs primarily through litter. Generally, it is not recommended that forests be cleared for energy plantations.

Where erosion has taken place or residues have not been returned to the soil, energy plantations offer opportunities to improve sequestering of carbon in the soil. When erosion occurs it differentially removes small clay particles and organic matter from heavier material. Soil carbon loss rates of 2-tons carbon per hectare-year or more are common but are merely translocated on the ground and not back into the atmosphere. Erosion prevention, in combination with organic matter inputs, make energy plantations a high priority candidate for soil stabilization and soil carbon increases. However, early plantation establishment phases will require special soil protection methods to be implemented.

Conversion of wetlands to drained plantation conditions will also reduce soil carbon inventories (Armentano 1980). Wetlands present a special case where organic matter accumulation is accelerated. Controlled drainage that permits hydroperiods during critical seasons should reduce soil carbon losses but may reduce plantation productivity and leaf litter input to the soil carbon pool. Numbers fluctuate too widely to quote but these sites are very important in soil carbon management.

The Net Sequestration of Carbon in Short-Rotation Plantations

Short-rotation plantations will generally be displacing agricultural land use so any differences that exist between the carbon inventory of these two uses at equilibrium equates to carbon sequestering potential. Comparison is difficult because there are so many variations to agricultural practices. Plantation effects on carbon are more consistent. Calculation of differences has serious limits due to great variation in land use history, soil type, and climate.

An attempt was made to characterize the main state variables and associated rate constants for short-rotation plantations (figure 6). Values were estimated from various literature sources and are in need of serious validation on a site by site basis. They represent average annual values, not the peaks and troughs in annual or rotation cycles. Thus they represent average values over a wide landscape.

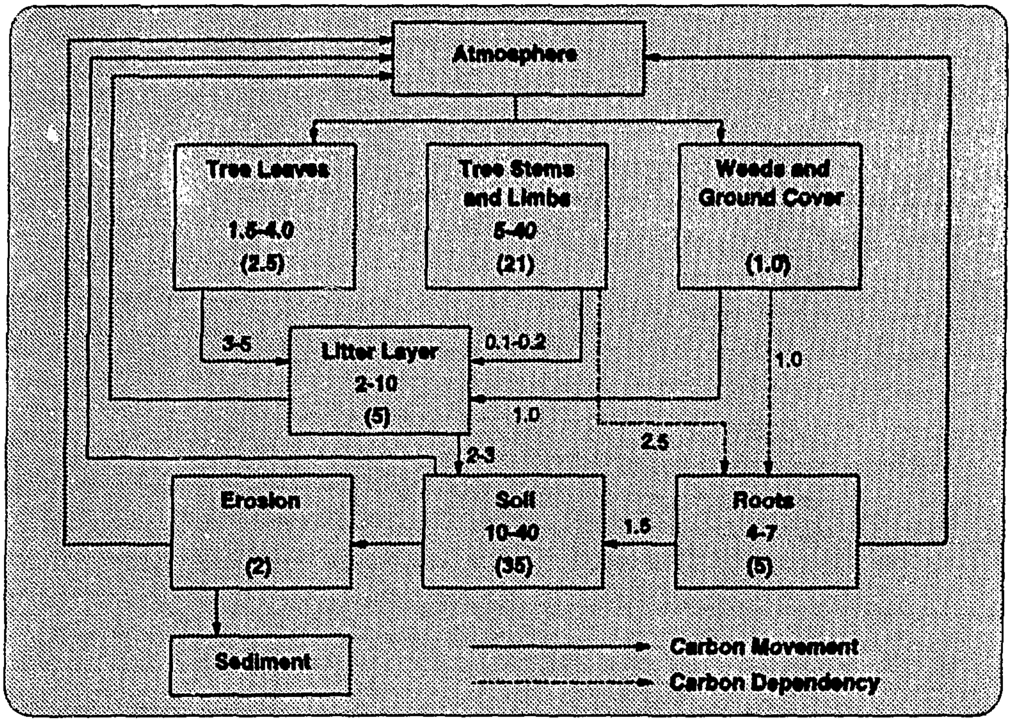
Mean annual inventories of carbon components in energy plantations vary significantly by species, rotation age, and soil type. Table 1 compares the estimated average carbon in the plantation state variables to those for an agricultural row crop. The points of greatest contrast concern tree stems and branches, the litter layer, and soil. Leaves, roots, and weeds account for only small differences. The conclusion is that short-rotation plantations under sustained management will eventually contain 30 to 40 more tonnes of carbon per hectare compared to row crop agriculture. If this equilibrium were to take 40 years, no advantages in sequestering would be expected after that time. Plantations would begin significant sequestering benefits in the second and third year after establishment. Benefits would accrue from litter layer formation, tree stem biomass development, and soil organic carbon buildup. After 6 to 10 years when average stand stem and root carbon have reached their maximum, further benefits will accrue in the form of increased soil carbon. Finally this will taper off as an equilibrium is reached. This equilibrium would take 20 to 50 years to attain.

Table 1. A comparison of hypothetical carbon levels (tonnes per hectare) for three land uses demonstrates the significance of stems, litter, roots, and soil carbon.

	CROPLAND	6-YEAR ROTATION PLANTATIONS	MANAGED FORESTS
LEAVES	4.0	2.5	2.5
STEMS	-	21.0	70.0
WEEDS	0.5	1.0	2.0
LITTER	0.5	5.0	15.0
ROOTS	2.0	5.0	10.0
SOIL	25.0	35.0	45.0
	32.0	69.5	144.5

Very short-rotation (annual harvest) plantations differ from agricultural row crops not so much in the above-ground biomass as in the formation of a litter layer and increased soil carbon. This is provided that leaf biomass is left on the site. The carbon sequestering benefit is perhaps half that of 6 year rotations or about 15 tonnes of carbon per hectare over an indefinite period.

Figure 6. Annual Carbon Inventories and Fluxes (tonnes/ha) for a Hypothetical 6-Year Rotation Plantation are Dominated by Stems, Litter, and Soil Carbon



(Numbers in parentheses are used in later comparison)

As a reminder, these figures will vary greatly between climates, soil types, and the type of land use being displaced. The figures are also in desperate need of validation and should only be considered as preliminary estimates.

Carbon Recycling and Displacement of Fossil Fuels

Fossil Fuel Use for Plantations

Fossil fuel use is dependent on the characterization of the plantation system itself. For example, an evaluation in the US (Wright et al., 1990) characterized short-rotation energy crops as:

Harvests on a 6-year rotation;

Two coppice harvests (18-year stand life);

Annual yield of 6.3 to 10 tonnes of carbon per hectare-year before production, harvest, handling, and storage losses (5.0 to 8.2 tonnes after losses);

Average annual per hectare fertilizer applications of 50 kg N, 15 kg P, and 15 kg K (not necessarily applied annually);

Weed control the first two years of each harvest cycle;

Annual pesticide application; and

Harvest, transport, and storage requiring fossil fuel use.

This characterization generated fossil fuel emissions at a rate of about 0.29 tonnes of carbon per hectare-year. Advanced energy plantation technology contributes about 0.40 tonnes per hectare-year, the increase caused principally by the harvest, transportation, and storage of 64% more biomass harvested per hectare.

This 0.29 tonnes a year is a perpetual carbon cost compared to a plantation carbon sequestering rate that averages about 1 tonne per hectare-year for about a 40 year period and no more. Stated more succinctly, energy plantations will act as a minor net sink for carbon for about 75 to 100 years. Thereafter, due to fossil fuel inputs for plantation management, plantations will be a net source of carbon at a rate of 0.29 to 0.40 tonnes per hectare year. If energy from the plantations was used to manage the plantations, the system could be a perpetual sink for carbon. These figures point to the value of energy plantations in avoiding the added emissions from fossil-fueled facilities rather than for sequestering carbon.

Shorter rotation lengths and/or less biomass harvested per hectare will slightly increase fossil fuel use and their emissions on a per hectare basis primarily due to harvest costs. Smaller, more energy efficient equipment will counteract this effect and effectively increase total fossil fuel emissions only by a trace.

Displacement of Fossil Fuels

Coal contains about 38% more energy per tonne than wood (Tillman 1978). Higher than normal bark to wood ratios can cause this figure to be lower. Conventional wood-fired electric generating plants operate at about 25% efficiency. New technologies incorporating gasification blends may achieve 31 to 33% efficiency (Ostlie) or 35 to 42% (Williams, et al.). Coal-fired systems operate at 31 to 34 efficiency while new technologies may raise this to parity with future wood-fired efficiency. Marland (1983) and Wright et al (1990) calculated the total carbon emissions per GJ based on the total extraction, transport, and utilization systems for short-rotation wood and coal. Their numbers were 24.65 kg C/GJ for coal and 25.32 kg C/GJ for wood.

Wright, et al (1990) considered all the inputs and outputs and assumed the plantations were able to utilize all the stack-emitted carbon dioxide in the regrowth that was necessary to feed the conversion facility. An excess of the amount needed to supply the facility is grown to account for losses in the harvest, transportation and storage phases. The land needed for the plantation then is a function of those losses and the conversion efficiency of the facility. Assuming a balance in carbon losses from such things as wood decay and stack emissions as well as the carbon sequestered in harvestable growth, their results showed that using plantation-fired system resulted in 0.29 to 0.40 tonnes per hectare-year net emission of carbon. Using coal resulted in net 5.22 to 8.62 tonnes carbon per hectare-year more than the plantation-fired systems. The study assumed credit only for recycling carbon and not for any permanent plantation carbon sequestration in the soil and inventory of trees. As previously discussed, if soil carbon sequestering and initial inventory buildup were considered in the equation, there would be no net carbon emission from a plantation-fired electric generating system for perhaps 75 to 100 years.

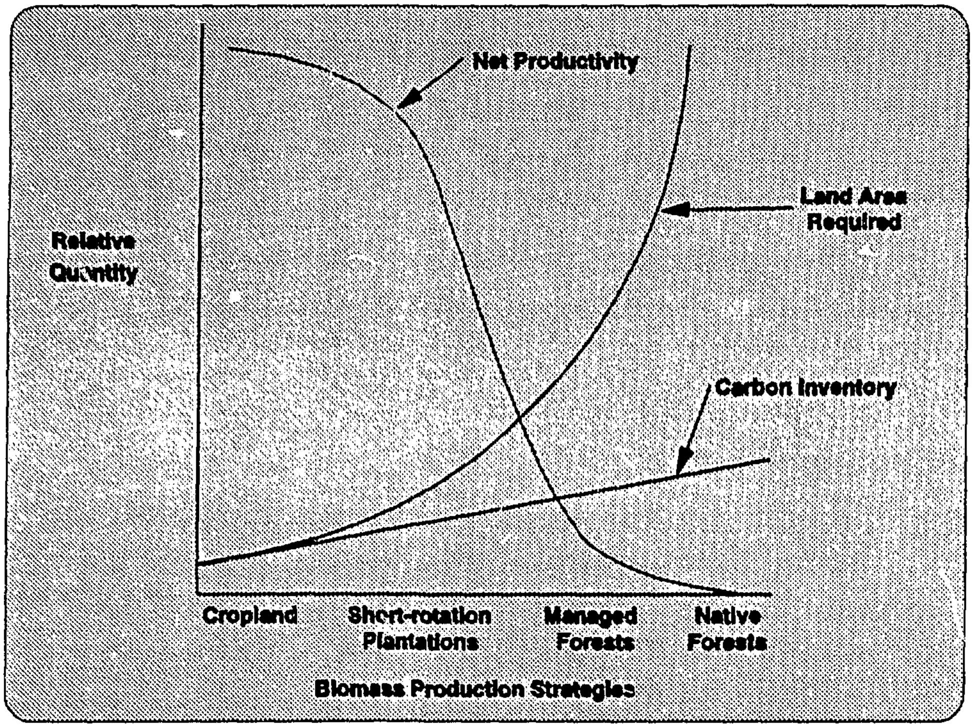
Net Changes in Landscape Carbon Inventories

Forestry, Agriculture, Energy Plantations

Any biomass-using energy facility will utilize its cheapest available biomass first. Beyond wastes and residues, this will involve harvesting low quality forests. Inventories in these forests may be 70 to 170 tonnes carbon per hectare. Growth of these forests, once cut, will usually not exceed 1 to 2 tonnes carbon per hectare-year. Soil carbon may drop by 7 to 10 tonnes per hectare over a few years then gradually begin to recover. Litter layers will probably decline and then recover. These forests harvested on a 60 to 90 year rotation may contain perhaps twice the total organic matter on the average that plantations do and slightly less than uncut forests.

Of native forest areas placed under management about an average of 0.25 to 0.5 tonne carbon per year net emission rate over many stands may occur for the first 90 years with a net even balance thereafter. This is because the average inventory of forest, litter, and soil carbon will be reduced. In addition, the land area and time involved for sustained biomass production to replace fossil fuel is very large (4 to 6 times larger than for energy plantations). This all assumes a facility's life can be extended to 90 years and fossil fuel used for forest management is not significant. Figure 7 compares biomass production strategies and shows the minimization of land area requirements and carbon inventory.

Figure 7. A Close Relationship Exists Between Different Sustainable Biomass Production Strategies, Carbon Inventory, and the Amount of Land Needed to Satisfy Feedstock Demand



Selective cutting of unmerchantable and low quality trees removes less biomass, increases productivity somewhat, eventually raises forest inventories, and may result in very slight declines in soil carbon. The trade-off is that 3 to 4 times more land will be affected compared to complete harvests, the cost of wood per ton will be significantly higher, and much of the low grade forest resource will be economically inaccessible.

The conclusion is that it is not generally a good idea to utilize native forests for energy production due to negative carbon balances and the large area of land affected (Harmon et al 1990). They may be better used for long term carbon sequestering and to fulfill energy feedstock needs in emergencies. However, the large amount of biomass on these sites make them attractive sources of energy. Forest low-grading may affect the same area of land as plantations harvested for energy each year. Energy low-grading of forests, in contrast to energy plantations, may be a one-time event for a particular tract so many more hectares will eventually be affected.

The reason this is being brought to attention is that land area, carbon sequestering, fossil fuel displacement, habitat quality, and sustainable biomass energy practices form a complex web of interactions on the landscape. The relative role of energy plantations is to temporarily increase carbon sequestering over agricultural land use, focus sustained recycling of energy carbon on a limited land base, and help increase carbon sequestering on forest lands over the long run.

From the standpoint of net carbon emissions, it is important that energy plantations be established on cropland and pastureland capable of yielding adequate plantation production. Plantations could enable a net increase in carbon sequestering of over 30 tonnes per hectare over cropland and perhaps 20 tonnes over well managed pasture, fossil fuel inputs not withstanding. Significant carbon sequestering benefits would be gained in converting drained cropland on wetland sites to undrained plantations. Increases in soil carbon inventories would be anticipated. Conversely, draining agricultural wetlands for energy plantations would result in a near-zero change in net carbon inventory. However, the stored carbon would be above ground rather than below.

Obviously the mix of agricultural and forested land available for energy supply, carbon sequestering, and energy plantations around a given energy facility will affect the landscape's carbon sequestering and fossil fuel displacement capability. Influential in this pattern is the land's productivity potential, the facility's size and conversion efficiency, and the alternative competitive uses for land and biomass.

Issues of Scaling, Prices, and Land Use

Larger scaling of biomass energy conversion facilities is desired by utility management as an efficiency enhancer and a larger satisfier of base load energy demands. Since the biomass procurement radius is nearly fixed in road and railroad distance and perhaps less fixed for barge transport, upscaling facilities pushes biomass prices up and increases the intensity of biomass production nearest these facilities and their cheapest transportation corridors. These same transportation corridors will be sought by other biomass users. It is anticipated that wide landscapes under extensive management will be imposed upon by intensively managed corridors of energy plantations and other biomass production uses - a hybrid system of agricultural, forestry, and energy infrastructure. The role of plantations as a source of biomass energy in industrialized nations may be one of base load supply along with biomass wastes and residues. For environmental reasons, existing forest biomass may only be a resource during critical periods. The implications of this are that use of agricultural land will be significantly altered by energy plantations, which is good for carbon sequestration. Also, the role of existing forests in supplying energy feedstocks will be diminished from many commonly held expectations. This is also good from the carbon sequestration position.

In developing countries energy plantations cannot be expected to have the same characteristics. Demands for multiple uses for firewood, fodder, centralized energy production, and soil stabilization will be high. A multitude of issues will push plantation production onto marginal, eroded sites. Productivity rates will be lower per tree and per hectare-year. And transportation distances will be severely constrained. The role of carbon sequestration in plantations may be very significant but will vary from the simplified monocultural systems and native forest systems in industrialized regions. These forces will generally limit the extent of economically competitive plantations to moist productive regions. Needs for soil stabilization through tree planting will offer opportunities for biomass energy options on less desirable sites.

A study for plantation establishment and carbon sequestration in SubSaharan Africa concluded that this method of carbon sequestration, compared to agroforestry and forestry management, offered the least benefit and most expense to sequestering carbon. However, it still remained an integral part of a larger continental plan. Plantations comprised about 10% of the 0.2 billion tonnes of potential carbon sequestration in the region. This was nearly completely confined to areas having more than 1000 mm precipitation per year.

Some Regional and Global Considerations for Energy Crops

Net carbon emissions to the atmosphere are nearing 7 billion tons per year. Based on 1987 UN data, about 5.8 billion tons comes from fossil fuel burning, most of the rest comes from deforestation and agriculture (forest and soil sources). Today's temperate forests may actually be a sink for carbon.

Energy plantations can affect the trends in all these numbers directly and indirectly. Use of energy plantations can help avoid some forest degradation and deforestation, particularly in developing tropical countries where most of the net deforestation and degradation is now occurring. Total global sequestering benefits from the plantations and improved native forests could approach perhaps 0.5 to 0.7 billion tons/year (for 10 to 20 years) while reducing deforestation. These activities together might increase soil carbon inventories by perhaps another 0.1 billion tons C/year over the next 30 years. These are highly speculative numbers needing much more verification.

Plantations could also be used to avoid some of the future increases in fossil fuel use. This merely acts to slow the increase in fossil fuel emissions of carbon. Significant displacement of existing fossil fuel use is not anticipated.

Net carbon sequestering benefits should be most realized from the moist temperate and tropical regions of the world where significant agricultural land is under some kind of cultivation. Countries offering the greatest plantation sequestering potentials are China, the EEC, United States, Brazil, Soviet Union, Zaire, India, Southeast Asia, and Central America. These countries together may account for more than 80% of the 0.6 to 0.7 billion ton global potential for sequestering carbon as a result of plantation development.

Conclusions

Short-rotation energy plantation offer some short-term carbon sequestering benefit when displacing agricultural land use. This benefit is primarily in the form of increased wood, soil, and litter organic matter. The increased carbon storage may range from 10 to 55 tonnes per hectare for plantations of 2 to 10 year rotations, respectively. Average carbon sequestered is above 30 tonnes per hectare, not withstanding fossil fuel use for plantation management. Including fossil fuel use assumptions, short-rotation plantations would provide low level net emissions after 75 to 100 years of operation. The time required to reach maximum equilibrium sequestration per hectare may be 20 to 50 years in temperate regions due to soil carbon storage phenomena. This rate is generally believed slower in boreal regions and faster in the tropics.

Many variables affect the quantity and timing of carbon sequestration in plantations. This is further complicated by the severe lack of carbon data on litter, soil, roots, and erosion for energy plantations and the vast differences that exist between sites. Estimates were made of carbon content in the major state variables of the system from a wide array of agricultural and forestry literature. Rate constants between variables were much more difficult to determine and require much more study.

The role of short-rotation plantations in affecting atmospheric carbon goes far beyond their capacity to sequester carbon. Plantation deployment will affect existing native forest sequestering potentials and the capacity for energy plantations to avoid some fossil fuel combustion. These far outweigh sequestering benefits. Clearing of forests for plantations has a strong negative effect on carbon sequestering. It is important that carbon sequestering in energy plantations not be removed from the context of general landscape changes in carbon inventories.

World-wide benefits of plantations and their secondary effects on native forests could potentially involve nearly leveling off of total global carbon emissions for a period of perhaps 10 to 20 years. The potential for actually reducing atmospheric carbon concentrations through plantations is negligible and is far outweighed by the potential from conservation of fossil fuels and naturally regenerating forest systems. The use of plantations as sustainable, nonshifting production systems is critical in conserving natural forests many times larger in area in moist temperate and tropical environments.

Further research is needed on plantation carbon sequestration, greenhouse gases that may be emitted from plantations, and full cycle production and conversion processes to increase the accuracy of observations presented here. This will require the integration of site-specific, landscape, and global perspectives on energy plantation deployment and carbon studies.

Recommendations for IEA/BA Future Work

1. Organize cooperative data collection methodologies and data needs to better define carbon cycling in short-rotation plantations for energy.

2. Encourage full systems analysis (upstream and downstream combined analysis) of alternative conversion systems for their impact on carbon cycles and other greenhouse gases.

3. Investigate the interrelationship between forestry, energy forestry, and agriculture through land use modeling and energy analyses.

4. Determine what preparations and responses to anticipate in energy forestry in response to increased carbon dioxide in combination with moisture changes and other atmospheric events (heat, air pollution/inversions, storm intensities).

5. Generate biomass energy strategies to incorporate carbon cycling and fossil fuel avoidance more than carbon sequestration itself.

6. Assess carbon cycling and sequestering options in energy feedstock plantations which improve sequestering estimates and capabilities, especially with respect to weed control, microorganisms, roots, and litter buildup.

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