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Soil Carbon Changes for Bioenergy Crops

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ACRONYMS AND ABBREVIATIONS

ac	acre
ANL	Argonne National Laboratory
Btu	British thermal unit(s)
C	carbon
CO_2	carbon dioxide
CRP	Conservation Reserve Program
dt	dry ton(s)
g	gram(s)
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation (model)
ha	hectare(s)
HF	heavy fraction
IPCC	Intergovernmental Panel on Climate Change
LF	light fraction
MBtu	million British thermal units
Mg	megagram(s) or metric ton(s)
MOM	mineral organic carbon
NC	north central
NE	northeast
NP	north plains
ORNL	Oak Ridge National Laboratory
POLYSYS	Policy Analysis System (model)
POM	particulate organic carbon
SE	southeast
SC	south central
USDA	United States Department of Agriculture
yr	year(s)

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EXECUTIVE SUMMARY

Bioenergy crops, which displace fossil fuels when used to produce ethanol, biobased products, and/or electricity, have the potential to further reduce atmospheric carbon levels by building up soil carbon levels, especially when planted on lands where these levels have been reduced by intensive tillage. The purpose of this study is to improve the characterization of the soil carbon (C) sequestration for bioenergy crops (switchgrass, poplars, and willows) in the Greenhouse gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (Wang 1999) by using the latest results reported in the literature and by Oak Ridge National Laboratory (ORNL). Because soil carbon sequestration for bioenergy crops can play a significant role in reducing greenhouse gas (GHG) emissions for cellulosic ethanol, it is important to periodically update the estimates of soil carbon sequestration from bioenergy crops as new and better data become available. We used the three-step process described below to conduct our study.

Step 1: Bioenergy Crop Cultivation. The results of an ORNL economic analysis (based on the POLYSYS model) were used to determine crop yields, geographic locations for bioenergy crop production, and land use changes.

The ORNL economic analysis assumed the same price per million Btu (MBtu) for the three bioenergy crops, but because of slightly different energy densities among the three crops, the dollar per dry ton ($/dt) prices differ (Walsh et al. 2003; de la Torre Ugarte et al. 2002). For this analysis, we used $1.77/MBtu, which is equivalent to a price of $27.50/dt for switchgrass. At this price, by the year 2008, an estimated 6.2 million acres (producing 34.7 million dt/yr) of land currently in conventional crop production could be used more profitably for switchgrass production (Figure 1).

Switchgrass completely dominated the other two bioenergy crops on land currently cropped land. The U.S. average switchgrass yield was 5.6 dt/acre. About 60% of the potentially profitable switchgrass production occurred in the southern regions. We aggregated the switchgrass data from 305 regions to 5 regions that have similar geo-climactic conditions. No idle or pasture acres went into bioenergy crop production at the premised prices, although they do at higher prices. The analysis concluded that planting some bioenergy crops on Conservation Reserve Program (CRP) land would be profitable. However, we did not include the CRP land because the assumption that farmers would retain most of the CRP rental rates when growing bioenergy crops is not current farm policy and would require legislative changes. (A payment reduction equal to 25% of the annual rental payment applies during the year the acreage is harvested.) Moreover, the economic analysis considered two scenarios for promoting bioenergy crop cultivation on CRP land. Hybrid poplars dominated in one scenario and switchgrass dominated in the other.

Step 2: Soil Carbon Changes. We used the ORNL soil carbon model (Switchgrass Model v.1.1) to estimate regional soil carbon changes on a per hectare basis over time, based on the regional yield and land use data from Step 1.

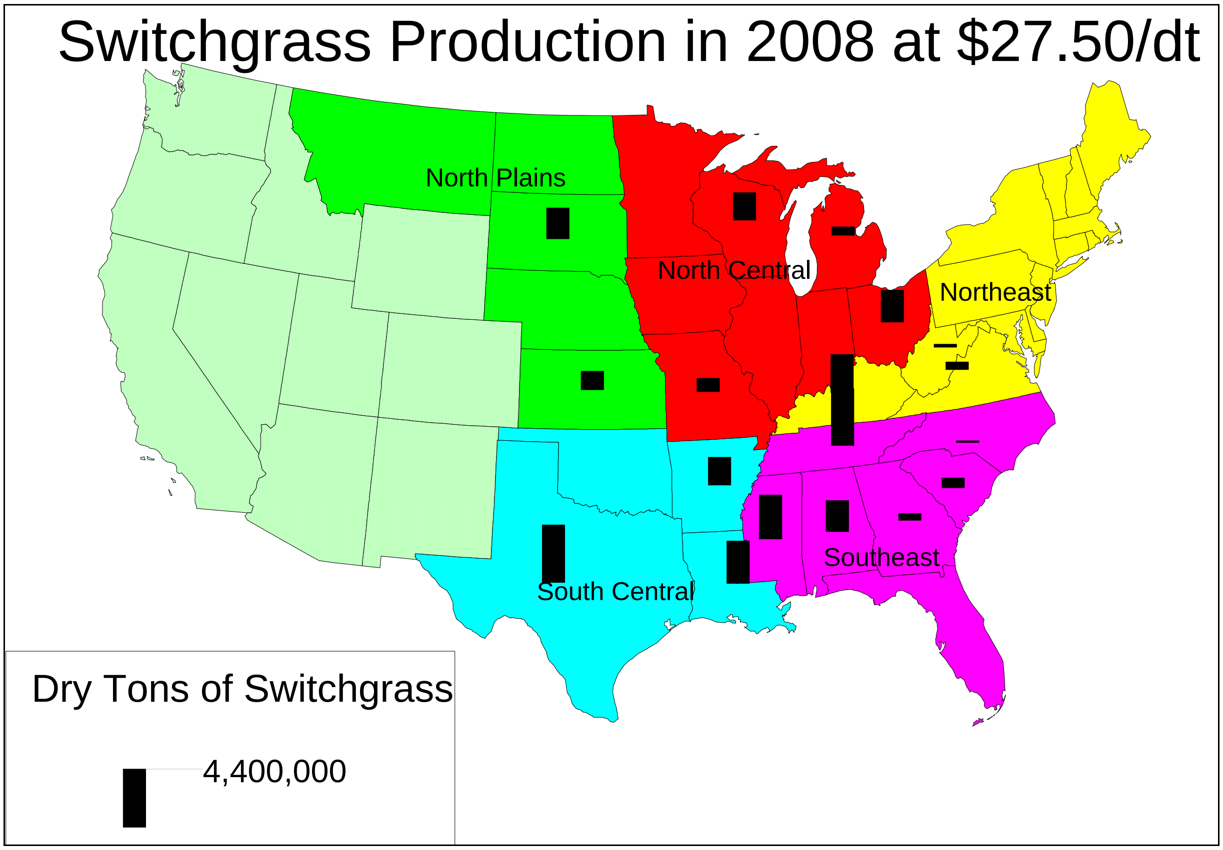

Figure 1 Switchgrass Production in 2008

The soil carbon changes for each of the regions shown in Figure 1 were estimated by the ORNL Switchgrass Model v.1.1 (Garten 2002) using recently updated data. Key input parameters include the mean annual temperature, the initial soil carbon stocks, and the soil carbon inputs. The soil carbon inputs come primarily from the root system and are assumed to be directly proportional to the average annual regional switchgrass production (harvested quantities for this analysis). We obtained year-by-year estimates of the soil and root carbon changes for the first 30 years of operation of a switchgrass farm, as well as eventual equilibrium values from ORNL (Table 1) (Garten 2002). The equilibrium carbon soil concentrations are typically reached, for all practical purposes, after about 125 years. The potential equilibrium soil content and the magnitude of the soil carbon gains are inversely related to temperature and directly related to the soil carbon inputs. Soil carbon gains are less in southern regions than in northern regions because of the high temperature differentials between the regions. Soil carbon gains are greater in the Northeast than in the North Plains because of the higher soil carbon input in the Northeast, even though temperatures are lower in the North Plains.

Step 3: Soil Carbon Changes per Unit of Biomass. We combined the results of Steps 1 and 2 to calculate soil carbon changes per unit of biomass as a function of time, and we aggregated regional data to a national estimate.

Table 1 Soil Carbon Levels for Switchgrass Planted on Cropland and Switchgrass Model Inputs

	North Plains (NP)	North Central (NC)	Northeast (NE)	South Central (SC)	Southeast (SE)
Mean Annual Temperature (°C) (model input)	7.6	9.2	11.3	13.2	16.5
Soil C Inputs (Mg C/ha) per Year (model input)	2.06	2.45	2.70	2.53	2.69
Weighted Average Switchgrass Yield (dt/acre)	4.59	5.48	6.02	5.65	6.00
Year	**Soil Mg C/ha for the first 40 cm of soil depth**				
Initial (model input)	37.9	49.0	40.3	47.8	38.5
10	44.6	55.9	48.3	50.9	39.7
20	52.8	63.7	57.2	55.6	42.3
30	59.5	71.5	64.3	59.4	44.4
Equilibrium	93.2	101.7	100.4	78.3	54.8
	Root Mg C/ha for the first 40 cm of soil depth				
Equilibrium	4.1	4.9	5.4	5.1	5.4

To estimate year-by-year soil carbon levels after 30 years, we fit a set of quadratic regression equations to the switchgrass soil carbon data as a function of time, with the additional requirement that each of the fit curves obtain its maximum at the soil carbon equilibrium value. The regression equations estimated that soil carbon equilibrium would be reached in about 125 years. We calculated the U.S. average soil carbon levels for switchgrass by weighting the regional soil carbon levels by the regional switchgrass production (Table 2).

The methodology used in GREET to assign carbon changes to a unit of biomass is to calculate the total soil carbon changes over the life of the bioenergy crop farm and divide the resulting value by the total biomass production during that period. Because the period that a switchgrass farm/rotation will persist is not known, we present the data averaged over different periods of time. We combined both the soil and root carbon, and then made two adjustments. First, the soil carbon changes were adjusted from 40 cm to 100 cm of soil depth by multiplying by 1.25, because empirical data suggest that about 80% of the soil carbon in the first 100 cm of soil depth is contained in the first 40 cm. The second adjustment accounts for the carbon that was in the root system of the displaced crop, which is estimated at 2 Mg C/ha. That is, we estimated the net root carbon gain that results from converting cropland to switchgrass. We converted the results to the units GREET uses: grams of carbon dioxide (CO_2) per dry ton of switchgrass. Finally, we estimated the carbon sequestration per unit of biomass for different discount rates by dividing the present value of the carbon gain from year 1 through year X by the present value of the biomass production from year 1 through year X (Table 3).

Table 2 Soil Carbon Levels for Switchgrass Planted on Cropland and Switchgrass Model Inputs (Mg C / ha for the first 40 cm of soil depth)

Year	NP	NC	NE	SC	SE	U.S. Average
Initial	38.0	49.0	40.0	48.0	39.0	43.3
30	59.5	71.5	64.3	59.4	44.4	57.2
50	72.2	84.5	78.1	66.7	48.5	65.7
60	77.3	89.5	83.7	69.7	50.1	69.1
90	88.3	99.4	95.5	75.9	53.6	76.2
100	90.6	101.0	97.9	77.1	54.2	77.6
Soil Carbon Gains						
30	21.6	22.5	24.0	11.6	5.9	14.1
50	34.3	35.5	37.8	18.9	10.0	22.6
60	39.4	40.5	43.4	21.9	11.6	26.0
90	50.4	50.4	55.2	28.1	15.1	33.1
100	52.7	52.0	57.6	29.3	15.7	34.5

Table 3 U.S. Average Soil CO_2 + Net Root CO_2 Gain per Unit of Biomass through a Given Year for Switchgrass Planted on Converted Cropland (g CO_2/dt biomass)

	Discount Rate		
Year	0.00%	1.00%	2.00%
30	191,704	194,173	196,432
50	170,875	175,736	180,438
60	161,385	167,837	174,080
90	134,148	146,973	158,999
100	125,274	140,749	155,025

We recognize that bioenergy crops may be grown on CRP land with the adoption of appropriate policies and sufficient incentives. Soil carbon concentrations on these acres are building up under current management practices. If bioenergy crops are planted on CRP land, the buildup of soil carbon is expected to continue; however, existing data are insufficient to determine whether conversion of CRP acres to bioenergy crop production will result in significantly higher or lower soil carbon levels compared with retaining these acres in their current uses with existing management practices. Until data are available, we take a conservative approach and assume no significant changes in soil carbon between the two options, because bioenergy crops such as switchgrass and poplar will typically replace other grasses and trees. We also want to point out that the POLYSYS model shows that idle crop and pasture lands can be profitably used for switchgrass production at higher switchgrass prices. However, the current soil carbon content of these lands depends on when they were last used for crop cultivation, and very little data on this topic are available. High-quality data on current soil carbon levels are essential to estimating the soil carbon gains that would result from converting these acres to energy crop production. In developing input values for GREET or similar models, researchers need to establish a scenario relating the amount of ethanol produced to the amount of feedstock produced from each land use type (e.g., crop land, idle land, pasture land, and CRP land).

INTRODUCTION

Carbon sequestration in terrestrial ecosystems can be defined as the net removal of CO_2 from the atmosphere into long-lived pools of carbon. The pools can be living, aboveground biomass (e.g., trees); products with a long useful life created from biomass (e.g., lumber); living biomass in soils (e.g., roots and microorganisms); or recalcitrant organic and inorganic carbon in soils and deeper subsurface environments. The Kyoto Protocol acknowledges the use of agricultural sinks for greenhouse gas (GHG) mitigation (e.g., in Article 3.4 [Kyoto]), but at this time, an international consensus on how to formulate a framework to account for stored carbon has not been reached. Bioenergy crops, which displace fossil fuels when used to produce ethanol, biobased products, and/or electricity, have the potential to further reduce atmospheric carbon by building up soil carbon levels, especially when planted on lands where soil carbon levels have been reduced by intensive tillage. (Converting native sod and forest lands to agricultural use results in a loss of soil carbon.)

The relationship between soil carbon levels and crop productivity is well known, and much of the past effort in the soil carbon area has focused on improving agricultural practices for croplands. But recently, a number of studies have focused on the relationship between bioenergy crops and soil carbon sequestration as a means of reducing atmospheric carbon dioxide (CO_2). Care must be taken when extrapolating the results of these studies because of the lack of longitudinal data; measurement differences among the studies; the influence of locale-specific factors, such as land quality and climate conditions; and the variety of plants used. Nevertheless, some broad-based conclusions from these studies can be drawn, and researchers have begun developing soil carbon models for bioenergy crops. These activities are still in their early stages, and the accuracy of soil carbon estimates will improve over time as new empirical data become available.

The purpose of this study is to improve the characterization of soil carbon sequestration for bioenergy crops in the Greenhouse gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed at Argonne National Laboratory (Wang 1999) by using the latest results reported in the literature and by Oak Ridge National Laboratory (ORNL). When bioenergy crops are used to produce cellulosic ethanol, GREET calculates a significant (70–85%) reduction in life-cycle GHGs compared to gasoline, with 7–15% of the reduction coming from soil carbon sequestration. Thus, it is important to accurately estimate soil carbon sequestration from bioenergy crops.

SOIL CARBON CYCLE

Figure 2 shows an overview of the soil carbon cycle for an agricultural system. Plants absorb CO_2 from the atmosphere to provide carbon for both aboveground and belowground biomass growth. Carbon input to the soil comes from the root exudates and mortality, aboveground litter,

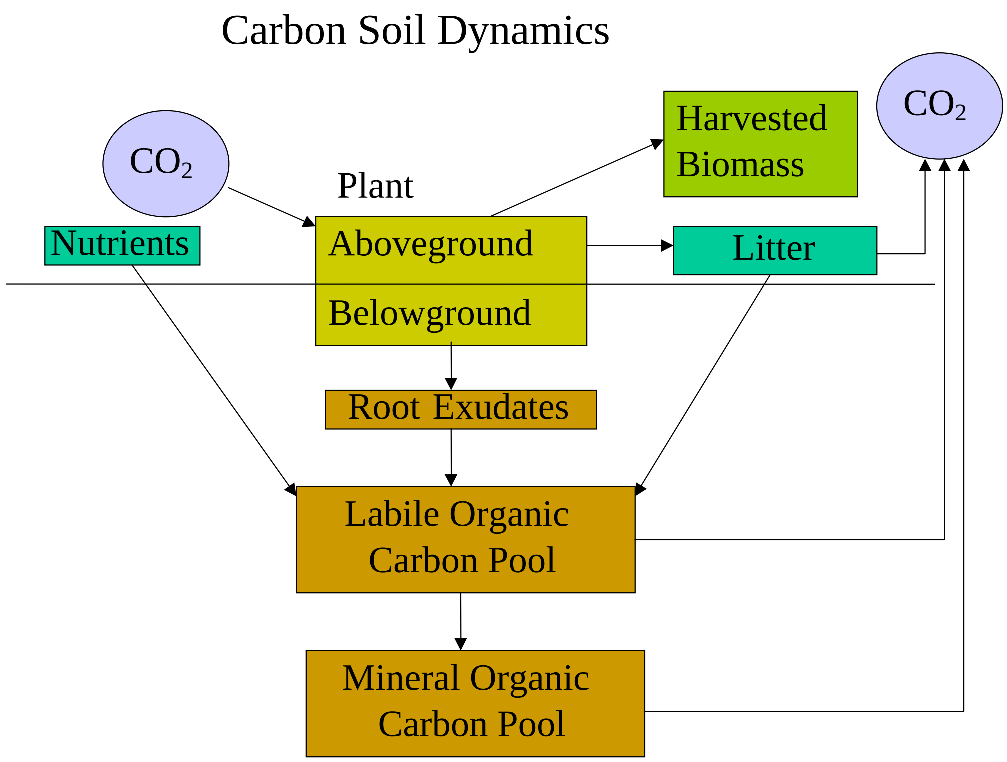

Figure 2 Soil Carbon Dynamics

and nutrients added to the soil. Important parameters are root turnover times and the percent of the added biomass that is carbon. In many cases, the bulk of the organic carbon matter input comes from the root system; this is especially true if the aboveground biomass is harvested. As the litter decomposes, some of the carbon is released into the atmosphere as CO_2, and some is deposited in the soil. Newly deposited soil organic matter undergoes decomposition and enters the labile pool as particulate organic matter (POM). Soil microbes act to degrade the particulate organic matter; the decomposition rate is affected by temperature, soil moisture, nutrient additions (particularly nitrogen), etc. The turnover time for the labile pool is typically a few years, but may be less than a year. As the organic matter in this pool decomposes, some of it is released back to the atmosphere as CO2, and some of it is humified and becomes part of the mineral organic matter (MOM) pool. The majority of the soil organic material is found in this pool, which has a turnover time on the order of decades. Soil carbon losses also occur from wind and water erosion. Erosion losses increase with cultivation and can be significant. The POM and MOM are sometimes referred to as the light-fraction (LF) and heavy-fraction (HF) organic matter, respectively.

A third carbon pool, which is not shown, is very stable, with turnover times of 1,500 to 3,500 years. Its presence is suggested by soil carbon-14 measurements, but measurement techniques to isolate it have not been developed. This so-called stable pool is thought to consist of nearly inert LF organic components, such as charcoal, and chemically recalcitrant organomineral HF complexes, but it is not well understood. In the short- to mid-term time periods, the interaction of the stable pool with the other two pools is minimal, and the carbon content of this pool is relatively constant.

Soil carbon levels are a function of many factors including:

- Climatic conditions such as temperature and moisture,
- Soil type,
- Type of vegetation,
- Biomass yield,
- Farming and management practices,
- Land topography and wind conditions, and
- Initial soil carbon content (for estimating changes over time).

Climatic conditions, particularly temperature and rainfall, have a large effect on soil carbon levels, which tend to decrease with higher temperatures and increase with higher moisture content. At higher temperatures, organic matter decomposes faster, and the rate of soil carbon oxidization increases, resulting in a greater release of CO_2 to the atmosphere. Higher moisture content increases biomass growth (increased soil organic matter input), promotes greater root penetration (stores carbon at greater depths), and moderates soil temperatures. Some soil types can accommodate greater carbon concentrations than others. For example, clayey soils tend to have greater carbon concentrations than sandy soils.

Soil carbon provides structure for the soil, increases water retention, and promotes deeper root penetration. All of these factors are associated with increased biomass yields. Conversely, a greater biomass yield can increase the soil organic inputs, which increases soil carbon levels. Erosion can have a major effect on soil carbon levels, because carbon concentrations are much higher near the surface. Higher soil carbon levels promote water retention, which reduces soil loss caused by water erosion. Land topography and wind conditions are important. Flat lands are less subject to erosion from winds and runoff from rains than inclined lands

For lands with significant vegetation, soil carbon levels are highest for forest lands and lowest for croplands. Soil carbon levels for native, undisturbed grasslands and lands planted with native grasses (such as switchgrass) fall in between these two extremes. If switchgrass yields are increased through research, crop selection, genetic modification, etc., their soil carbon levels could exceed those of native grasslands, because of their larger rootstock systems. Soil carbon levels for hybrid poplars and willows used as bioenergy crops tend to be lower than those of native forest lands, because the plants are harvested on a periodic basis and because new saplings are planted every 6 to 10 years rather than regenerating the stumps. If research efforts aimed at developing fast-growing varieties of woody bioenergy crops are successful, an increase in soil carbon levels could also occur. The extent of the increase will depend, in part, on how the root/shoot ratio (i.e., the ratio between the aboveground and belowground biomass) changes.

Farming practices have a major impact on soil carbon levels. Deep plowing increases the loss of soil carbon by disturbing the soil structure, introducing more oxygen into the soil, exposing buried carbon matter to moisture and microbes, increasing soil temperatures, and through the mechanical release of some CO_2. Soil losses from both wind and water erosion increase significantly with tillage. The use of no-till or limited-till practices can help increase soil carbon content in depleted soils. Figure 3 illustrates the range of soil loss that can occur with different plowing methods. The amount of irrigation, nutrient addition, and residues left on the ground also affect soil carbon levels.

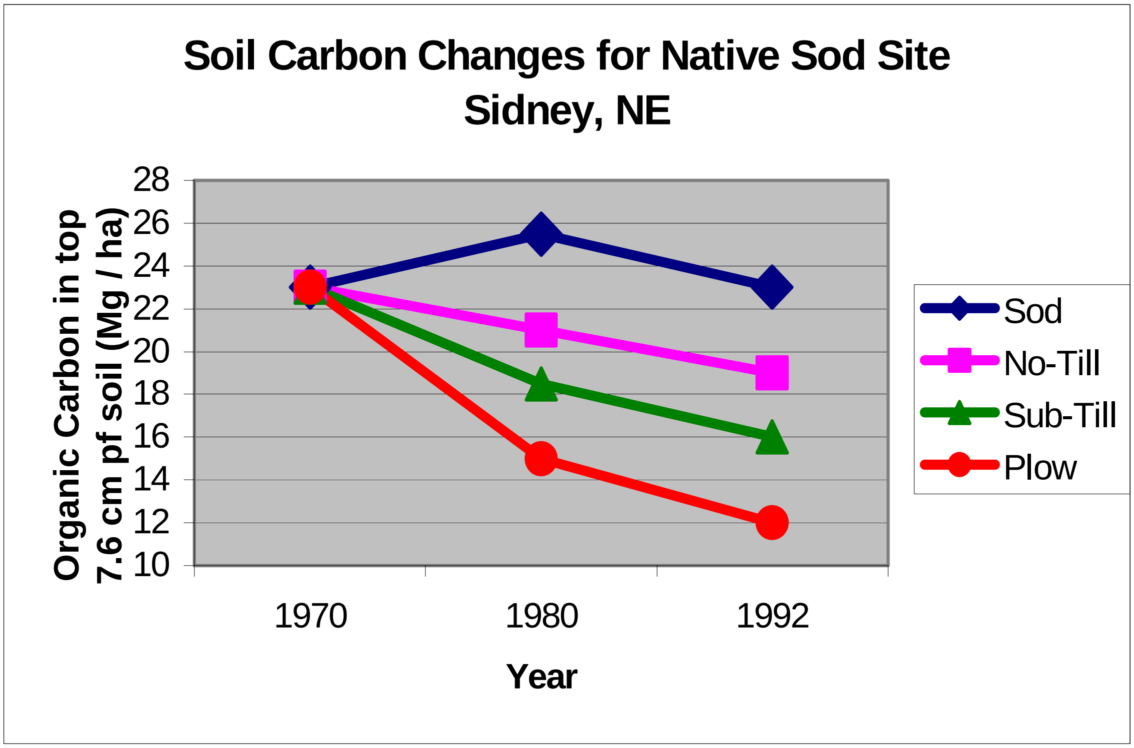

Figure 3 Example of Soil Carbon Concentrations for Different Plowing Practices (Wilhelm 2001)

In a simplified representation — assuming that all factors, such as crop yield, temperature, rainfall, farming practices, etc., remain constant — the soil carbon concentration eventually reaches an equilibrium value. Figure 4 illustrates this phenomenon for several different crops. To interpret this figure, select the line associated with a particular crop (e.g., corn). Points above the x-axis represent conditions of positive humus change. Moving along the line downward and to the right corresponds to an increase in soil carbon concentrations over time. (The time dimension is not shown in the figure.) An equilibrium condition is approached as the carbon added to the soil from plant growth approaches the carbon lost from the soil through respiration. Conversely, at a point below the x-axis, the carbon added to the soil is less than the carbon lost through respiration, and in time, the soil carbon concentration will decrease. If you change crops (e.g., from corn to soybeans), you transition from the corn line to the soybean line, and the soil carbon content will approach a new equilibrium level, depending on how long the soybean production continues.

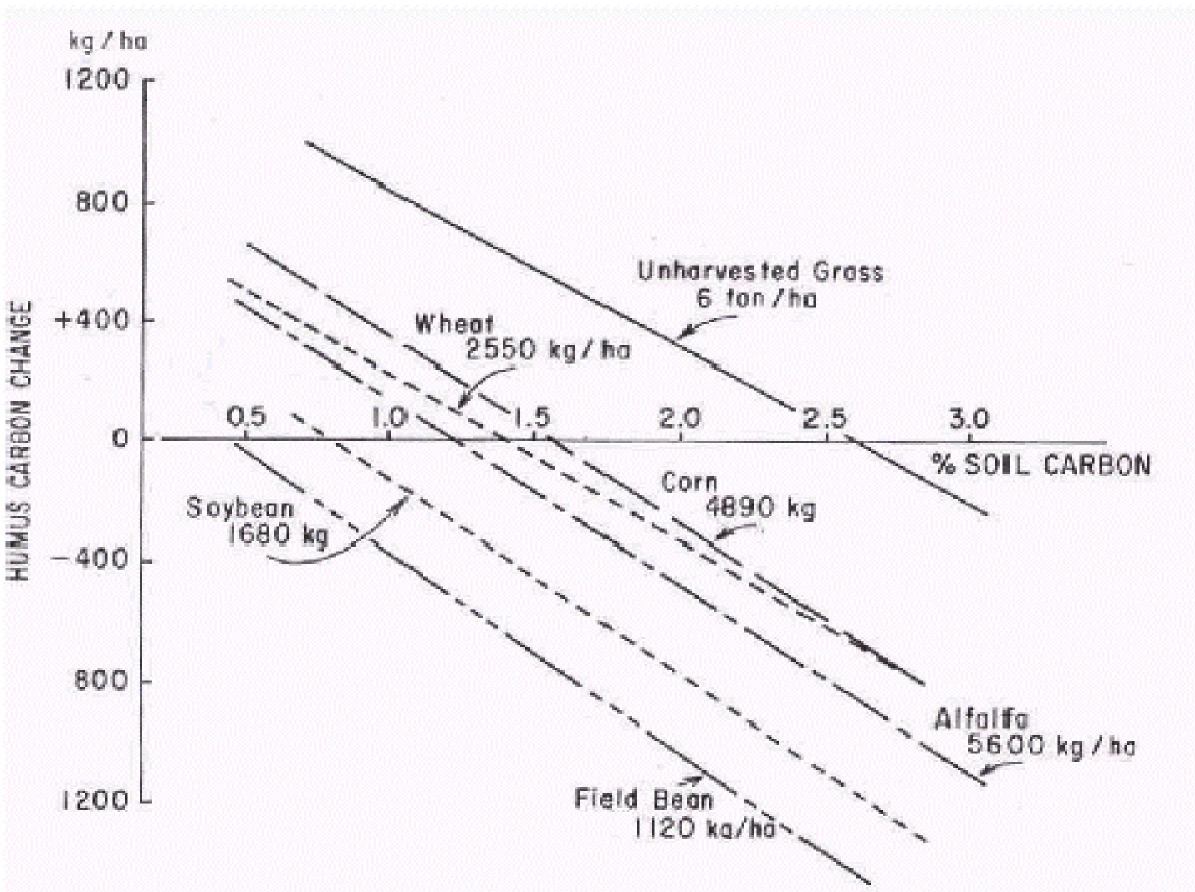

Figure 4. Soil Carbon Relationships for Different Crops (Jawdy 2001)

The linear relationship depicted in Figure 4 can be interpreted as representing the differential equation dC/dt = A + rC, where dC/dt is the change in soil carbon over time, A is the carbon added to the soil at time t, C is the soil carbon content at time t, and r is the respiration/erosion factor (rC is the amount of carbon lost from the soil at time t). A more complex model would allow A and r to vary over time, but a constant representation is often used as a quick modeling tool because insufficient experimental data are available to estimate time-dependent functions for A and r. A more comprehensive representation would track multiple soil carbon pools with separate respiration/erosion factors for each pool, as well as the carbon flows between the individual pools, which is the approach used in the ORNL Switchgrass Model.

For a particular crop, a greater aboveground biomass growth is often correlated with a greater equilibrium soil carbon concentration, but other factors — such as the amount of biomass that is harvested and changes in the root/shoot ratio — are also important. The root/shoot ratio (i.e., the ratio of the aboveground to the belowground biomass) is often used to estimate root growth as a function of harvested biomass. For simplicity, the root/shoot ratio is frequently assumed to be constant over time when estimating projected changes in soil carbon, but the actual ratio can depend on management practices, which can divert growth to either the aboveground or the belowground biomass. For example, repartitioning, which provides more aboveground and less belowground mass, is a standard approach for increasing grain yields from conventional crops. (In some cases, there is a higher grain yield with less belowground biomass and less other aboveground biomass.) Improved yields attributable to greater pest and disease resistance may or may not be accompanied by an increase in root biomass. Parrish 2001 reports that, for select varieties of switchgrass, the biomass yield is greater when harvested twice per year than when harvested annually, but he did not observe any change in root mass. Ma, Wood, and Bransby (2000a) report that soil carbon levels can be lower, depending on the soil type, when switchgrass is harvested twice per year than when it is harvested annually. They suggest that this effect is similar to a grazing environment, in which a shift in carbon allocation from root growth to leaf growth occurs.

There are many ways to increase aboveground biomass production, some of which will have a positive effect on soil carbon concentrations. Nonetheless, it is well known that crop productivity generally improves as soil carbon levels build up in depleted soils.

CONCEPTUAL ISSUES ASSOCIATED WITH LAND USE CHANGES

The methodology used in GREET and by many other GHG modelers (e.g., Delucchi 2001) to account for changes in soil carbon when land use changes are involved is to calculate the difference between the soil carbon levels for the land used to grow the new crop and those associated with the land's original use. For example, if native grassland is converted to cropland (e.g., to grow corn for ethanol production), a net loss in soil carbon occurs. On the other hand, if switchgrass is planted on existing cropland, soil carbon levels increase. For bioenergy crops, the soil carbon changes are allocated to a unit of harvested biomass, because the ultimate goal is to assign the soil carbon change to a unit of ethanol, electricity, or biobased product. An underlying assumption in both these examples is that, with the change in land use, soil carbon concentrations will transition from the original equilibrium level to a new equilibrium level.

A major challenge in estimating soil carbon changes over long periods is developing an appropriate baseline to compare net soil carbon changes resulting from changes in management practices, land use patterns, policies, etc. over time with those that would result if existing conditions were maintained. Obtaining high-quality data for land where soil carbon concentrations are relatively stable is difficult enough, but it can be further complicated in cases in which soil carbon concentrations are still changing under current land use practices. Consider a case in which bioenergy crops are planted on CRP land. Soil carbon concentrations on these acres are building up under current management practices. If bioenergy crops are planted on CRP land, the buildup of soil carbon is expected to continue, but available data are insufficient to determine whether conversion of CRP acres to bioenergy crop production will result in significantly higher or lower soil carbon levels than maintaining these acres in their current uses and under their current management practices. Until these data are available, analysts can take a conservative approach and assume no significant changes in soil carbon will occur between the two options, as bioenergy crops such as switchgrass and poplars will typically replace other grasses and trees.

The CRP example also illustrates another difficulty in developing a land use base case. The government provides incentives (rental rates) for farmers to plant grasses and trees on CRP land. Except for land designated for specific conservation practices, CRP land contracts are executed for a 10- to 15-year period. When estimating land use changes over long time periods, analysts must make assumptions about the disposition of this land when these contracts expire. In addition, a change in government policies — for example, subsidizing bioenergy crops but not current CRP land use practices — could change the land use base case.

In developing a methodology to account for soil carbon credits, it is absolutely essential to clearly define the system boundaries. One option is to compare a world with and without ethanol production from bioenergy crops. If we adopt a conservative approach for CRP land (i.e., converting the land to bioenergy crops would produce no significant changes in soil carbon relative to current practices), we would not credit any soil carbon changes to the bioenergy crops.

A second option is based on the fact that there is a benefit in either land use case, and this benefit should be counted in either case. Here, the boundary is drawn around each land use activity separately. The option could apply to a case in which the land is already converted to growing bioenergy crops. In this case, the alternative — to convert the land back to non-bioenergy-crop CRP land — would be soil carbon neutral. The point is that if there is a buildup of soil carbon, it should be counted, and once the land is converted to bioenergy crops, the previous land use no longer exists. It is important to recognize that the soil carbon buildup is gradual and occurs over a long period of time; it is not a one-time event that occurs with a land use change. After 20 years of operation, the bioenergy crop farm is still building up soil carbon and should get credit for the sequestration; in other words, the benefit is no longer associated with a land use practice that ceased 20 years ago.

Which option we use can depend on what question we want to answer and how we account for the carbon changes. If we want to look at a policy question, such as what soil carbon benefits will accrue from converting CRP land from current management practices to bioenergy crops, the answer may be that no net soil carbon sequestration benefit occurs between the two options. But once the land is converted, we should count the soil carbon benefits, because now we have changed our land use base case. This option would be appropriate for use in a carbon credit accounting system; such a system may come out of the Kyoto protocol. The question now is whether the soil carbon credit should be assigned to the CRP program or to the production of ethanol. For example, if the CRP program allows a choice between current management practices and growing bioenergy crops, some analysts argue that the soil carbon credit should be assigned to the CRP program and not the production of ethanol. Conversely, if the CRP program were modified so that incentives are offered only for the production of bioenergy crops, the conversion of the land to bioenergy crops would be directly tied to the production of ethanol, power, or biobased products.

We want to comment on a further difficulty in developing a land use base that incorporates our expectations about future land use practices. As we noted above, we could analyze a policy change that would encourage the growth of bioenergy crops on CRP land (e.g., through an economic analysis). The analysis could show that some CRP land could be profitably converted to bioenergy crops. Now assume the policy is adopted: the question now is how does that policy affect our base case? If we use the same economic analysis as before, we would be predicting a new future based upon the new policy — one that involves the conversion of some CRP land to bioenergy crops at some point in the future. Should that then become our base case, i.e., does our base case allow for land use changes in the future?

A major difficulty in developing a verifiable and internationally accepted accounting system for assigning carbon credits for soil carbon sequestration is to ensure that soil carbon levels are not degraded in the future. This is a key issue that will have to be resolved in developing any international carbon accounting and trading system. For example, land can be converted from corn production to switchgrass production, and then back to corn production, which can result in a loss of the soil carbon buildup achieved during switchgrass cultivation. Similarly, carbon credits can accrue with no-till farming practices, but the benefit would be lost if the land is later converted back to conventional tillage. Changes in policy could result in significant CRP acres being returned to conventional crop production, resulting in significant changes in soil carbon. These considerations can be serious impediments to establishing a carbon trading system.

Alternatives to make the soil carbon sequestration benefits permanent (e.g., establishing land use covenants) have been suggested, but these alternatives are beyond the scope of this paper. In the examples given here, there is still a carbon reduction benefit, but it is temporary and the question becomes how do we account for it? Delucchi (2001) uses a present-value technique that calculates the carbon reduction benefit as the difference between the present value of the net carbon sequestered in the soil and biomass over the life of the bioenergy crop farm minus the present value of the net carbon returned to the atmosphere as CO_2 when the bioenergy crop production ceases. Both present-value calculations depend on the type of land use change involved: in the first case, the land use prior to planting bioenergy crops, and in the second case, the disposition of the land after bioenergy crop production ceases. The calculation, of course, depends on the choice of a discount rate. Delucchi uses 2%.

Many of the topics discussed in this section are beyond the scope of this project, but they are important issues that we want to raise for public discussion. For the purpose of this analysis, the baseline assumes that soil carbon levels on croplands remain unchanged from initial conditions, and that acres converted to bioenergy crop production remain in bioenergy crop production using the same management practices over the time period used in the analysis. We further assume, to be conservative and because of the lack of data, that no net carbon sequestration benefit occurs for bioenergy crops grown on CRP land.

APPROACH

The approach used for estimating soil carbon sequestration for bioenergy crops is summarized below:

- *Step 1: Bioenergy Crop Cultivation.* The results of an ORNL economic analysis were used to determine crop yields, geographic locations for bioenergy crop production, and land use changes.

- *Step 2: Soil Carbon Changes.* The results of the ORNL soil carbon model were used to estimate regional soil carbon changes on a per hectare basis over time, based on the regional yield and land use data from Step 1.

- *Step 3: Soil Carbon Changes per Unit of Biomass.* We combined the results of Steps 1 and 2 to calculate soil carbon changes per unit of biomass as a function of time, and we aggregated regional data to a national estimate.

Each of these steps is described in more detail below.

Step 1: Bioenergy Crop Cultivation

The regional information for bioenergy crop production (crop yields, acres planted, and land use changes) was derived from an ORNL economic analysis of bioenergy crops (Walsh et al. 2003; de la Torre Ugarte et al. 2002). In a joint project with DOE and the United States Department of Agriculture (USDA), ORNL and the University of Tennessee modified the Policy Analysis System (POLYSYS) model (Tiller et al. 1999), a U.S. agricultural sector model used by USDA, to include three bioenergy crops (switchgrass, hybrid poplar, and willow). POLYSYS models 305 U.S. production regions and includes all of the major cropland categories (cropped, idle, pasture, CRP); major conventional crops and livestock; food, feed, export, and industrial demand; as well as carry-over stocks. The POLYSYS model allocates land between existing uses and bioenergy crops on the basis of relative profitability. The model incorporates a quasi-rational expectations approach that allows farmers to incorporate, into their current planting decisions, expected future changes in conventional crop prices that may result from wide-scale production of bioenergy crops. Bioenergy crops compete not only with existing land uses, but also with each other for the same land. The analysis of bioenergy crop production on CRP acres assumed that farmers forfeit 25% of their rental rate in exchange for the right to harvest and sell bioenergy crops. The forfeiture occurs only in the year in which the CRP acres are harvested. The CRP analysis evaluated two separate management practices: one to provide high biomass productivity and one to provide high wildlife diversity.

The economic analysis assumed the same $/MBtu price ($1.77) for the three bioenergy crops, but because of slightly different energy densities among the three crops, the $/dry ton prices differ. For switchgrass, this assumption results in a price of $27.50/dry ton. At this price, by the year 2008, an estimated 6.2 million acres (producing 34.7 million dry tons annually) of land currently in conventional crop production could be more profitable in switchgrass production. Switchgrass completely dominated the other two bioenergy crops in terms of production on currently cropped land. No idle or pasture acres went into bioenergy crop production at the premised prices. With higher prices for bioenergy crops; however, planting switchgrass on some of these acres could be profitable. (At $37.50/dry ton, for example, the potential switchgrass production by the year 2008 from these acres is about 16 million dry tons compared with approximately 97 million dry tons from currently cropped acres.) Although these lands are not included in the carbon soil analysis, we want to point out that the data on the current soil carbon content for these lands are very sparse and so the content is difficult to estimate. For example, the soil carbon content for pastureland will depend on when the land was last used as cropland.

The analysis also concluded that planting some bioenergy crops on CRP land would be profitable. We did not include the CRP land because the assumption that farmers would retain 75% of the CRP rental rates for growing bioenergy crops is not current farm policy and would require legislative changes. Without this assumption, planting bioenergy crops on CRP lands would not be profitable at the premised prices. Moreover, we also did not want to select a specific scenario because the bioenergy crop that could be most profitably planted on CRP land varied by scenario — poplars for the wildlife management scenario and switchgrass for the production management scenario. A key reason for this divergence was that switchgrass harvesting was limited to every other year in the wildlife management scenario. In neither scenario were acres allocated to willows.

It should be noted that the U.S. Congress enacted legislation to establish a Biomass Pilot Program on CRP acres (Public Law [PL] 106-78, Section 769), and USDA is currently in the process of implementing the program. According to the statute, up to six projects are authorized for the harvesting of biomass to be used for bioenergy. The land must be enrolled for at least 10 years, and no acres can be harvested more than once every 2 years. A payment reduction equal to 25% of the annual rental rate will apply during the year the acreage is harvested. The terms of the pilot project are similar to those of the ORNL wildlife diversity scenario. The point here is not to speculate about future CRP policies, but to note the necessity for keeping abreast of them. We are unaware of any studies that characterize soil carbon changes when bioenergy crops are planted on CRP land. Compared to continuing current CRP land practices, soil carbon levels could increase or decrease, as discussed above.

Our conclusions are based on an economic analysis for U.S. bioenergy crops, the assumptions made for that analysis, and current U.S. agricultural policies; they are highly dependent on the price paid for bioenergy crops. Offering higher prices for switchgrass will lead to substantially different land use changes with potentially different soil carbon implications. Planting poplars or willows may be more economically attractive under different conditions or in other countries. For example, poplars are very attractive for fiber uses, and perhaps a combined fiber/energy use could change the economics change substantially. Nonetheless, we feel comfortable with concentrating on switchgrass for now, because at the low premised prices for bioenergy crops, the estimated quantities of switchgrass, in conjunction with agricultural residues, are more than sufficient to supply an emerging cellulosic industry. Moreover, poplars will likely command a higher price by the paper and pulp industry than the one premised here.

Converted switchgrass acres were aggregated into five geographic regions with similar climatic conditions as shown in Table 4 and Figure 5. These regions correspond to the regions used by ORNL soil analysts for modeling soil carbon changes. At the premised price of $27.50/dt, about 31%% of the switchgrass production occurred in the Southeast and about 28% in the South-Central region.

Step 2: Soil Carbon Changes

The soil carbon changes for each of the regions identified in Step 1 were estimated in the Switchgrass model v.1.1 (Garten 2002) using recently updated data. Key input parameters

Table 4 Switchgrass Planting and Harvest Data for 2008 (switchgrass planted on cropland; $27.50/dt)

Region	Switchgrass Acres Planted	Switchgrass Production (dt)	Weighted Average Yield (dt/ac)	Total Switchgrass Acres (%)	Total Production (%)
North Plains	830,960	3,757,558	4.59	13.4	10.8
North Central	1,133,177	6,186,256	5.48	18.3	17.8
Northeast	615,650	3,703,607	6.02	9.9	10.7
South Central	1,712,622	9,656,267	5.65	27.7	27.9
Southeast	1,900,948	11,365,530	6.00	30.7	32.8
Total	6,193,357	34,669,218	5.60	100.0	100.0

Regions:
North Plains — MT, ND, SD, NE, KS
North Central — MN, WI, IL, IA, MO, MI, IN, OH
Northeast — KY, WV, VA, MD, PA, DE, NJ, NY, VT, NH, ME, MA, CT, RI
South Central — OK, TX, AR, LA
Southeast — TN, NC, SC, GA, AL, MS, FL

Sources: Walsh et al. 2003; de la Torre Ugarte et al. 2002

include the mean annual temperature, the initial soil carbon stocks, and the soil carbon inputs (Table 5). The soil carbon inputs come primarily from the root system and are assumed to be directly proportional to the average regional switchgrass production (harvested quantities for this analysis). The carbon gain projections produced by the Switchgrass Model are very dependent on these parameters. The estimates for the initial soil carbon stocks are less certain than the mean annual temperatures and are expected to improve as more data become available. The Switchgrass Model framework is streamlined compared to the more detailed Century model, a widely used soil sequestration model. Recent analyses indicate that the predictability from two-compartment models, such as the Switchgrass Model, can be similar to that of more complex, multi-compartment models (Bolker et al. 1998), especially for the type of scoping analysis presented here. We are assuming that the selected regions have similar characteristics (e.g., climatic conditions, soil types, initial carbon levels for different land use types) for modeling soil carbon changes or, more specifically, that the regional average characteristics used in the analysis are sufficient to provide reasonable estimates of average soil carbon changes in each region.

The model internal parameters (e.g., the root turnover rates, the flows from the POM pool to the MOM pool) were empirically derived (Garten and Wullschlager 2000). To estimate turnover times for the POM and MOM pools, soil samples were taken at several research plots, and a 2-mm sieve was used to remove the course root material. A 0.053-mm sieve was then used to separate the MOM (less than 0.053 mm) from the POM pool. The flows into and out of the MOM and POM pools were estimated by means of stable isotopic analyses.

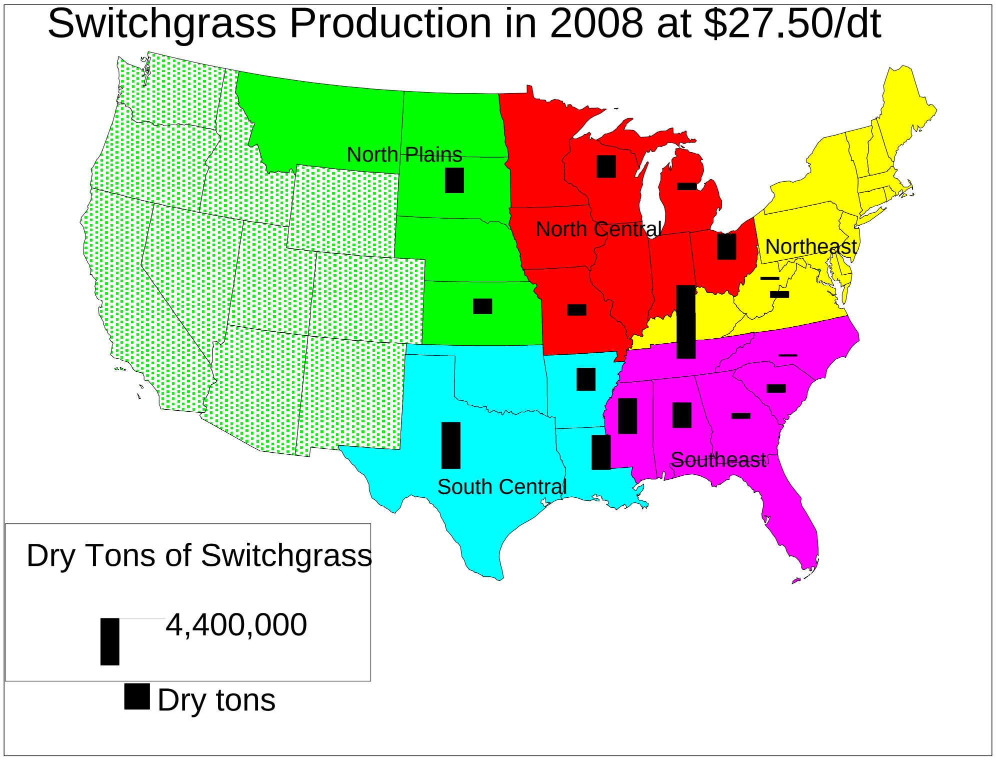

Figure 5 Switchgrass Production in 2008

Table 5 Key Switchgrass Model Input Parameters

Region	Mean Annual Temperature (ºC)	Initial Soil C Stocks (Mg C/ha to first 40 cm of soil depth) Under Cultivated Land	Soil C Inputs (Mg C/ha per year)
North Plains (NP)	7.6	37.87	2.06
North Central (NC)	9.2	48.99	2.45
Northeast (NE)	11.3	40.31	2.70
South Central (SC)	13.2	47.84	2.53
Southeast (SE)	16.5	38.50	2.69

Source: Garten (2002)

The Switchgrass Model reports soil and root carbon levels for the first 40 cm of soil depth. Root carbon levels are reported separately because some researchers report only soil carbon levels. Table 6 summarizes the soil carbon levels through the first 30 years of planting switchgrass on Cropland, as well as the equilibrium carbon levels. Garten (2002) supplied 30-year model run data, as well as the equilibrium soil carbon values. The initial soil contents range from 38 to 49 Mg C/ha. Table 7 shows the gains in soil carbon from the initial year. The soil carbon gains at 30 years range from 6 to 24 Mg C/ha. At equilibrium, they range from 16 to 60 Mg C/ha, corresponding to gains in soil carbon of 42% to 146%. The magnitude of the regional gains is inversely proportional to regional temperatures and directly related to the soil carbon inputs, which for our analysis are proportional to the switchgrass production. Soil carbon gains are lower in southern regions than in northern regions, because of the high temperature differentials between the regions. Soil carbon gains are greater in the Northeast than in the North Plains because of the higher soil carbon input in the Northeast, even though temperatures are lower in the North Plains.

The root carbon values range from 4.1 to 5.4 Mg C/ha for the five regions (Table 8). The root carbon approaches an equilibrium value in about 10 years. At 30 years, the ratio of the root carbon to the soil carbon gain varies from 19% for the Northern Plains to 100% for the Southeast region. The average U.S. ratio is 53%. (The derivation of the average U.S. statistics is explained in the next section.) When the soil carbon reaches its maximum or equilibrium level, the regional ratios range from 7% to 34%, and the average U.S. ratio is 20%.

Table 6 Soil Carbon Levels for Switchgrass Planted on Cropland (Mg C/ha to the first 40 cm of soil depth)

Year	NP	NC	NE	SC	SE
Initial	37.9	49.0	40.3	47.8	38.5
10	44.6	55.9	48.3	50.9	39.7
20	52.8	63.7	57.2	55.6	42.3
30	59.5	71.5	64.3	59.4	44.4
Equilibrium	93.2	101.7	100.4	78.3	54.8

Table 7 Soil Carbon Gain for Switchgrass Planted on Cropland (Mg C/ha to the first 40 cm of soil depth)

Year	NP	NC	NE	SC	SE
10	6.7	6.9	8.0	3.1	1.2
20	14.9	14.7	16.9	7.8	3.8
30	21.6	22.5	24.0	11.6	5.9
Equilibrium	55.3	52.7	60.1	30.5	16.3
Percent (%) Gain at equilibrium	146	108	64	42	82

Table 8 Root Carbon and Ratios of Root Carbon to Soil Carbon

	NP	NC	NE	SC	SE	U.S. Average
Root carbon at equilibrium (Mg C/ha)	4.1	4.9	5.4	5.1	5.4	5.1
Ratio of root carbon to soil carbon gain at 30th year	19%	22%	22%	44%	100%	53%
Ratio of root carbon to soil carbon gain at equilibrium	7%	9%	9%	17%	34%	20%

Step 3: Soil Carbon Changes per Unit of Biomass

One methodology used in GREET to assign carbon changes to a unit of biomass is to calculate the total soil carbon changes over the life of the bioenergy crop farm and divide it by the total biomass production during that period. However, it is not known how long switchgrass farming will persist. Some researchers have suggested that switchgrass cultivation could continue indefinitely on the same land. On the other hand, some scoping analysis at ORNL using the POLYSYS model suggested that farmers may rotate land used for switchgrass to other crops and vice versa, based upon changing economic conditions. (The POLYSYS model analysis assumed a 10-year rotation cycle for switchgrass production.) To bracket the range of possibilities, we present cumulative averages for different years.

The soil carbon projections did not account for increases in harvest yields over time, which is a major goal of bioenergy crop research. As discussed earlier, increasing harvest yield may or may not lead to increased soil carbon levels on a per-unit-of biomass or even on per-unit-of-land basis. If soil carbon levels increase at the same rate as the biomass increases, our estimates of the change in soil carbon sequestration per unit of biomass may be affected only modestly, because we are dividing a greater amount of soil carbon sequestered per hectare by a greater amount of biomass harvested per hectare over a period of time. Conversely, if the biomass increases are not accompanied by increases in soil carbon, our estimates of the change in soil carbon sequestration per unit of biomass will be too high.

The Switchgrass Model data we received contained year-by-year data for the first 30 years of continuous switchgrass production. We fit a set of quadratic regression equations to the soil carbon data as a function of time, with the additional requirement that each of the fit curves obtain its maximum at the soil carbon equilibrium value. We used these fit curves to estimate soil carbon changes on a year-by-year basis after 30 years. The regression R-squares were around 0.99. The regression fits indicated that the equilibrium soil carbon levels were obtained at around 125 years. We present the soil carbon data for up to the first 20, 50, 60, 90, and 100 years in the following tables. (The Intergovernmental Panel on Climate Control [IPCC] estimates the persistence of CO_2 in the atmosphere at about 100 years for the purpose of estimating global warming impacts.)

The regional soil carbon changes from Step 2 were aggregated to estimate an average U.S. soil carbon change by weighting the individual regional data by the percent of switchgrass production in each region. Table 9 shows the soil carbon levels for selected years, along with the percent of the equilibrium soil carbon level. For the U.S. average, the initial carbon levels are about 58% of the equilibrium value at 30 years, 74% at 50 years, and 97% at 90 years. The U.S. average gain in soil carbon is 14.1 Mg C/ha at 30 years, 22.6 Mg C/ha at 50 years, and 33.1 Mg C/ha 90 years (Table 10).

Table 9 Switchgrass Soil Carbon Levels on Converted Cropland (Mg C/ha for first 40 cm of soil depth)

Year	NP	NC	NE	SC	SE	U.S. Average
Initial	38.0	49.0	40.0	48.0	39.0	43.3
30	59.5	71.5	64.3	59.4	44.4	57.2
50	72.2	84.5	78.1	66.7	48.5	65.7
60	77.3	89.5	83.7	69.7	50.1	69.1
90	88.3	99.4	95.5	75.9	53.6	76.2
100	90.6	101.0	97.9	77.1	54.2	77.6

Percent of Equilibrium Soil Carbon

Year	NP	NC	NE	SC	SE	U.S. Average
Initial	41	48	40	61	71	58
30	64	70	64	76	81	74
50	77	83	78	85	88	84
60	83	88	83	89	91	88
90	95	98	95	97	98	97
100	97	99	97	98	99	98

Table 10 Cumulative Soil Carbon Gain through a Given Year for Switchgrass Planted on Converted Cropland (Mg C/ha for first 40 cm of soil depth)

Year	NP	NC	NE	SC	SE	U.S. Average
30	21.6	22.5	24.0	11.6	5.9	14.1
50	34.3	35.5	37.8	18.9	10.0	22.6
60	39.4	40.5	43.4	21.9	11.6	26.0
90	50.4	50.4	55.2	28.1	15.1	33.1
100	52.7	52.0	57.6	29.3	15.7	34.5

Table 11 presents the average soil carbon gain per year for the first 40 cm of soil depth through selected years. The average soil carbon gain per year for the first 30 years is 0.469 Mg C/ha. The average gain per year at 50 years is 0.453 Mg C/ha, only a slight decrease. At 100 years, it is 0.345 Mg C/ha, a decrease of about 26% from the 30-year value.

Table 11 Average Soil Carbon Gain per Year through a Given Year for Switchgrass Planted on Converted Cropland (Mg C/ha for first 40 cm of soil depth)

Year	NP	NC	NE	SC	SE	U.S. Average
30	0.720	0.750	0.800	0.387	0.197	0.469
50	0.685	0.710	0.757	0.379	0.200	0.453
60	0.656	0.675	0.723	0.364	0.194	0.434
90	0.561	0.560	0.613	0.312	0.167	0.368
100	0.527	0.520	0.576	0.293	0.157	0.345

Table 12 shows the root carbon gain for the first 40 cm of soil depth averaged per year for selected years. Because the rootstock mass, and hence, the carbon in the rootstock, approaches an equilibrium value after about 10 years, averaging over a longer time period just reduces the per-year contribution of the root stock. Table 13 shows the average soil and root carbon gain per unit of biomass through selected years.

Table 12 Root Carbon Averaged per Year through a given Year for Switchgrass Planted on Converted Cropland (Mg C/ha for first 40 cm of soil depth)

Year	NP	NC	NE	SC	SE	U.S. Average
30	0.137	0.164	0.180	0.169	0.179	0.169
50	0.082	0.098	0.108	0.101	0.108	0.101
60	0.069	0.082	0.090	0.084	0.090	0.085
90	0.046	0.055	0.060	0.056	0.060	0.056
100	0.041	0.049	0.054	0.051	0.054	0.051

Table 13 Average Soil Carbon Gain + Root Carbon for the First 40 cm of Soil Depth per Unit of Biomass through Selected Years for Switchgrass Planted on Converted Cropland (Mg C/Mg biomass)

Year	NP	NC	NE	SC	SE	U.S. Average
30	0.083	0.074	0.073	0.043	0.027	0.051
50	0.074	0.066	0.065	0.038	0.022	0.044
60	0.070	0.062	0.061	0.035	0.020	0.042
90	0.059	0.050	0.050	0.029	0.016	0.034
100	0.055	0.046	0.047	0.027	0.015	0.032

Two adjustments are made to the estimated soil and root carbon data for use in GREET. First the soil carbon changes are adjusted from 40 cm to 100 cm of soil depth by multiplying by 1.25 because empirical data suggest that about 80% of the soil carbon in the first 100 cm is contained in the first 40 cm (Garten 2002). The second adjustment accounts for the carbon that was in the root system of the displaced crop, which is estimated at 2 Mg C/ha (Bowman and Turnbull 1997). That is, we estimate the net root carbon gain that results from converting cropland to switchgrass. Table 14 shows the results.

Table 14 Average Soil Carbon Gain + Net Root Carbon Gain for First 100 cm of Soil Depth per Unit of Biomass through Selected Years for Switchgrass Planted on Converted Cropland (Mg C/Mg biomass)

Year	NP	NC	NE	SC	SE	U.S. Average
30	0.096	0.086	0.085	0.048	0.029	0.058
50	0.088	0.077	0.075	0.043	0.025	0.051
60	0.083	0.073	0.071	0.040	0.023	0.048
90	0.070	0.060	0.060	0.034	0.019	0.040
100	0.066	0.056	0.056	0.032	0.018	0.038

Economists use discount rates to calculate the present value of costs and benefits that occur over time. Present value analyses are also very useful for quantifying benefits that occur over long periods of time, especially when the benefits do not occur evenly over time. Such is the case with the soil carbon sequestration for switchgrass, for which the rate of sequestration is greater in the earlier years. However, such analyses introduce the problem of choosing an appropriate discount rate. Many researchers use a low discount rate (on the order of 1 to 2%) for these types of long-range problems. The approach used here is similar to the concept of a levelized cost used in engineering economics. The carbon gain per unit of biomass for discount rate R is defined as the present value of the carbon gain from year 1 through year X divided by the present value of the biomass production from years 1 through X. The present value formula for a series A_t is the sum of $A_t/(1+R)^t$, from year 1 to year X.

Figure 6 compares the soil carbon gains through year X for discount rates of 0 (no discount), 1%, and 2%. Through 50 years, the difference between a zero discount rate and a 2% discount rate is

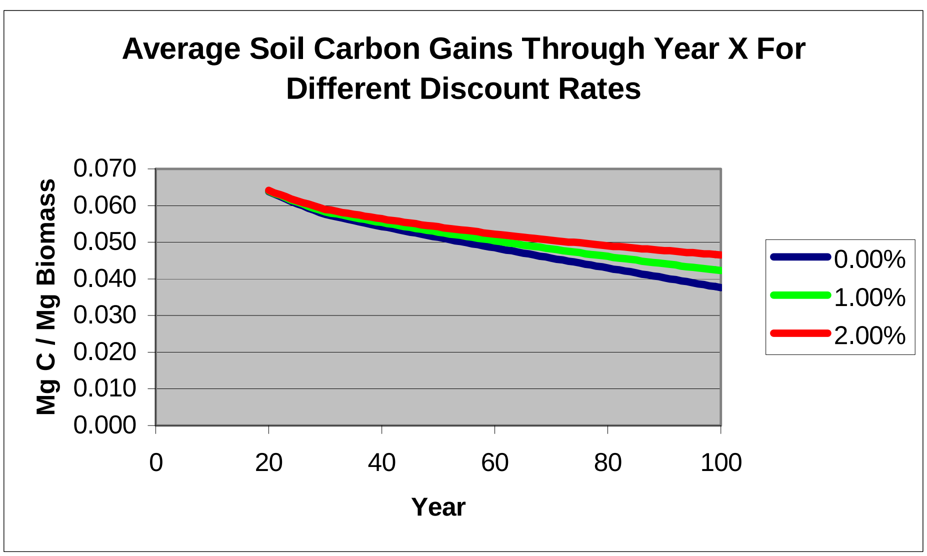

Figure 6 Average Soil Carbon plus Net Root Carbon Gain to 100 cm per Unit of Biomass through Year X for Switchgrass Planted on Converted Cropland

very small. At 100 years, the present value carbon gain for the 2% discount rate is about 25% higher than for a zero discount rate. A larger discount rate produces a higher benefit because the soil carbon increases are greater in the earlier years, while the biomass production is assumed to be constant over time.

The GREET units for soil carbon changes attributable to land use changes are grams of CO_2/dry ton of biomass. Table 15 presents these data for select years.

We recognize that bioenergy crops may be grown on CRP land with the adoption of appropriate policies and sufficient incentives. As noted earlier, we assume, to be conservative and because of the lack of data, that no net carbon sequestration benefit occurs for bioenergy crops grown on CRP land.

Table 15 U.S. Average Soil CO_2 + Net Root CO_2 Gain per Unit of Biomass through a Given Year for Switchgrass Planted on Converted Cropland (g CO_2/dt of biomass)

	Discount Rate		
Year	**0.00%**	**1.00%**	**2.00%**
30	191,704	194,173	196,432
50	170,875	175,736	180,438
60	161,385	167,837	174,080
90	134,148	146,973	158,999
100	125,274	140,749	155,025

ABOVEGROUND BIOMASS

The carbon sequestration estimates presented in this paper do not account for the carbon sequestered in any aboveground biomass. This is a reasonable approximation for switchgrass, which is harvested annually, but may not be appropriate for woody energy crops, such as hybrid poplars, that are harvested on 6- to 12-year cycles.

A simple rule for estimating the amount of carbon stored in a harvested crop is to multiply the carbon in the harvested biomass by the number of years in the harvest cycle and divide the resulting number by two (Delucchi 2001). This rule assumes that the crop grows uniformly over the harvest cycle and that it is harvested and used at the end of the cycle. (Because the growth pattern for short-rotation woody crops typically follows an S-shaped curve, a uniform growth assumption overestimates the time-averaged carbon sequestered in the harvested biomass.) This is a one-time gain when land is converted to a new crop; it will last as long as the land is used for the new crop. Any land use change must, of course, take into account the carbon in the displaced crop, and so there may be either a gain or a loss.

To illustrate the application of this rule, assume that 40% of the harvested hybrid poplar biomass is carbon and that the harvest cycle is 10 years. Then, the carbon sequestered in the above biomass is 2 Mg C for every Mg of biomass harvested. This can be a significant source of carbon sequestration, depending on how much carbon is in the displaced crops. The per-year benefit, however, depends on the length of the period over which the average is taken (Table 16). At the 30-year mark, the per-year average carbon sequestered in the aboveground biomass for the hybrid poplar example is greater than the per-year average carbon sequestered in the soil and root system for switchgrass; but at 50 years, the reverse is true.

Table 16 Example of Average Carbon Sequestered in Aboveground Biomass through Given Year for Hybrid Poplar with a 10-Year Harvest Cycle

Average Mg C/Mg Biomass Over Harvest Cycle	Years	Mg C/Mg Biomass
2	30	0.067
2	50	0.040
2	60	0.033
2	90	0.022
2	100	0.020

For switchgrass, which is harvested annually, the carbon sequestered in the aboveground biomass is only 0.2 Mg C for every Mg of biomass harvested, which is similar to the carbon in the displaced crop. For example, we have estimated switchgrass yields at 5.5 dry tons per acre for a U.S. average. In 2001, the U.S. average corn yield is about 135 bushels per acre or 3.87 tons per acre (not dry tons). The stover weight is approximately the same, so the total aboveground biomass for corn is about 7.74 tons per acre. The moisture content in a standard bushel of corn is 15.5% (Hirning et al. 1987) and that of corn stover is between 20% and 25% (Walsh 2002), so the aboveground biomass for corn plants is 6.27 dry tons per acre — slightly more than the assumed switchgrass yields. Aboveground biomass quantities for other major food crops in the United States are less than that of corn on a per acre basis. For example, the U.S. average yield for soybeans in 2001 was 39.6 bushels per acre, or 1.19 tons per acre. The soy stover weight can be 1.5 times the soybean weight (Wilhelm 2001), so the combined soybean plus stover yield is about 2.97 tons per acre. The moisture content in a standard bushel of soybeans is 13% (Hirning et al. 1987), and using that as a conservative estimate for the soy stover, we calculated the aboveground biomass for soy plants at 2.63 dry tons per acre.

DIFFICULTIES IN OBTAINING SOIL CARBON ESTIMATES FOR BIOENERGY CROPS

Very little long-term data on soil carbon changes are available because bioenergy crops are a relatively new concept. Comparing results from different studies is difficult because of the diversity of climates, initial land conditions, soil type, management practices, biomass yields, etc. The lack of uniformity in soil carbon measurements (e.g., measurement techniques, soil sample depths, adjustments made to account for root volume [primarily an issue for trees]) presents serious problems when comparing the results of different studies. Study results are often expressed in terms of carbon concentration per volume, and analysts must make assumptions about soil bulk density in order to estimate carbon content per unit area. Similarly, analysts must make assumptions about carbon concentrations as a function of depth in order to convert estimates of soil carbon levels reported at one depth to another depth.

One difficulty with interpreting the results in the literature is that they are often expressed as the average change in carbon per unit area per year, but the number of years over which the average is taken varies significantly among studies. Very little data exist on equilibrium carbon levels when bioenergy crops are involved. Very short-term studies can pose problems, because there may be some initial soil carbon loss in the first few years when the land is converted to bioenergy crops (Ma, Wood, and Bransby 2000b; Grogan and Mathews 2001). One reason for this loss may be the clearing of existing vegetation prior to establishment of bioenergy crops, as was the case with some of the switchgrass experiments, but other factors may also play a role. Further research in this area is needed.

Some data are reported in terms of average annual percentage increases in soil carbon. These data are particularly hard to interpret because analysts need to know the initial soil carbon concentrations in order to calculate the soil carbon gains.

SELECT SOIL CARBON ESTIMATES

In this section, we present select estimates of soil sequestration reported in the literature. We do not include switchgrass here, because Garten (2002) has compiled and incorporated the most recent data in the switchgrass soil carbon data that he provided to us.

Grogan and Matthews (2001) report that the experimental data for short-rotation coppice plantations indicate that soil carbon gains can range from 0 to 1.6 Mg C/ha per year. In their own analysis for willows, they estimated a gain of 0.5 Mg/ha per year, but cautioned that the analysis was very preliminary and site-specific. Their analysis relied heavily on long-term soil organic carbon measurements at the Geescroft Wilderness site at Rothamsted, UK. The site, which had previously been in arable cropping for several centuries, was fenced off in the 1880s and left unattended. Initially, the area was colonized by damp-loving grass species, but by 1957, it had reverted to woodland, and most grassland species had disappeared. Soil samples were taken in 1883, 1904, 1965, and 1985. The data show a steady increase in soil organic carbon in the 0–23 cm layer from 28 Mg C/ha to more than 60 Mg C/ha, a mean annual increase of 0.33 Mg C/ha per year. Grogan and Mathews also reviewed available soil sequestration models and concluded that CENTURY seemed to have the best potential for adaptation to bioenergy crop systems because of its integrated plant-soil approach and the availability of specific forestry subroutines.

Hansen (1993) reported soil carbon contents of poplar plantations established in the north-central U.S. on previously tilled agricultural prairie land compared to adjacent control grass and arable fields. The poplar-planted acres showed a net loss of soil carbon over the first 6 to 12 years. This loss was largely from the surface 30 cm of soil. Over the full 18 years of the study, however, soil carbon content to 1 m in depth increased at an average rate of 1.6 Mg per ha per year compared to control fields. This high rate of soil carbon sequestration may have been partly attributable to the inclusion of relatively deep soil horizons in the study. In particular, there was a substantial increase in the 30–50 cm soil layer that was attributed to tree root growth and associated carbon inputs to the soil.

While very little long-term data are available for bioenergy crops, a considerable amount are available for converting agricultural lands to trees and grasses. These data may be useful for understanding the effects of soil carbon changes for bioenergy crops, if the impact of harvesting the bioenergy crops is understood. Post & Kwon (2000) assembled a list of studies that reported soil carbon gains after agricultural lands were converted to forests and grasslands, and after making suitable conversions to put the data on a common basis, they estimated an average gain of 0.338 and 0.332 Mg C per/per year, respectively.

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