DOI: 10.1007/s00267-003-9108-3

Carbon Management Response Curves: Estimates of Temporal Soil Carbon Dynamics

TRISTRAM O. WEST*
GREGG MARLAND
ANTHONY W. KING
WILFRED M. POST
Environmental Sciences Division
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee 37831-6335, USA

ATUL K. JAIN
Department of Atmospheric Sciences
University of Illinois, Urbana-Champaign
105 S. Gregory Street
Urbana, Illinois 61801, USA

KENNETH ANDRASKO
U.S. Environmental Protection Agency
1200 Pennsylvania Ave. NW
Washington, DC 20460, USA

ABSTRACT / Measurement of the change in soil carbon that accompanies a change in land use (e.g., forest to agriculture) or management (e.g., conventional tillage to no-till) can be complex and expensive, may require reference plots, and is subject to the variability of statistical sampling and short-term variability in weather. In this paper, we develop Carbon Management Response (CMR) curves that could be used as an alternative to *in situ* measurements. The CMR curves developed here are based on quantitative reviews of existing global analyses and field observations of changes in soil carbon. The curves show mean annual rates of soil carbon change, estimated time to maximum rates of change, and estimated time to a new soil carbon steady state following the initial change in management. We illustrate how CMR curves could be used in a carbon accounting framework while effectively addressing a number of potential policy issues commonly associated with carbon accounting. We find that CMR curves provide a transparent means to account for changes in soil carbon accumulation and loss rates over time, and also provide empirical relationships that might be used in the development or validation of ecological or Earth systems models.

International initiatives to reduce net greenhouse gas emissions by sequestering carbon in the terrestrial biosphere have prompted the need for an accounting framework that records changes in carbon stocks associated with changes in either land use (e.g., forest to agriculture) or land management (e.g., conventional tillage to no tillage). Changes in carbon stocks following changes in land use or land management can be accounted for by either direct measurement or estimates based on similar changes measured elsewhere. Both approaches have some advantages and some disadvantages.

Measured values of soil carbon stocks can vary greatly over time, both inter- and intra-annually. This apparent variability may be due to sampling that is not sufficient to effectively overcome the natural, spatial variation in soil carbon; or it may be because of real changes in carbon content due to significant changes in weather patterns. This variability can make it difficult to determine, over the course of several years, whether the overall net change in soil carbon is positive or negative (West 2002). Additionally, direct measurement of changes in soil carbon requires the use of control plots to ensure that the observed changes in soil carbon are primarily due to the prescribed change in land use or land management.

Estimating changes in soil carbon based on a statistical representation of experimental data for similar changes in land use or land management elsewhere may prove to be more consistent and less costly than measuring changes directly. An estimate of soil carbon change might be a static value for the annual change in a carbon stock, or it might be a dynamic estimate calculated by using a comprehensive, process-based model.

Understanding the tradeoffs between directly measuring and estimating carbon stocks is important when considering development of a carbon accounting framework. Statistical estimates might be chosen over field measurements to yield more predictable changes in carbon and to reduce costs associated with direct

Published online December 15, 2003.

*Author to whom correspondence should be addressed, *email:* westto@ornl.gov

Table 1. Changes in land management that can increase soil carbon

Cropland[a]	Grassland or pasture[b]	Forest[c]	Wetland[d]
• Reduced tillage intensity	• Effective species selection	• Fertilization	• Restore previously drained wetlands (particularly abandoned agricultural land where drainage tiles remain)
• Increase rotation complexity	• Inclusion of legume	• Inclusion of legume	
• Inclusion of legume in rotation	• Manure management	• Erosion reduction	
• Reduce fallow period	• Earthworm introduction	• Agroforestry practices	
• Inclusion of winter cover crop	• Irrigation	• Conversion of cropland or pasture to forest	
• Efficient management of fertilizers, pesticides, and irrigation	• Fertilization		
• Erosion reduction	• Erosion reduction		
	• Conversion of cropland to grassland/pasture		

[a]Paustian et al. (1997), West and Post (2002).
[b]Conant et al. (2001).
[c]Heath et al. (2003), Post (2003).
[d]Whiting and Chanton (2001).

measurement. With respect to the use of estimates, simple empirical (statistical) relationships may be more practical, more functional, and more transparent than estimates based on complex simulation models.

Our objective is to summarize existing analytical data and use it to develop empirical relationships that represent temporal changes in soil carbon as a result of changes in land use and land management. A key focus of this paper is to examine how these empirical relationships could be used in carbon accounting systems and how they could address policy issues commonly associated with carbon accounting. We provide three examples that summarize experimental measurements to empirically show how soil carbon changes over time after a change in land use or land management. These empirical relationships are hereinafter referred to as Carbon Management Response (CMR) curves.

Houghton and others (1983) developed similar response curves to depict changes in carbon stocks following changes in land use. The Houghton curves were characterized by an initial maximum value of carbon, a carbon value following disturbance, a carbon value following recovery, and estimates of the time required to move from one carbon value to another. Updated response curves have been provided by Houghton and others (1987) and Houghton and Hackler (2001). The intent for further development of CMR curves is to focus on changes in carbon stocks that follow changes in land management strategies within existing ecosystems (e.g., reducing tillage in an agricultural system or use of organic fertilizers), while also improving estimates of changes in carbon stocks that typically follow changes in land use (e.g., conversion of forest to agriculture). Some examples of changes in land use and management that are expected to increase soil carbon stocks are provided in Table 1.

Carbon management response curves are currently being developed for changes in the management of agriculture, forest, grassland, and wetland ecosystems. We are focusing on soil carbon only. Since our initial CMR curves are based on a number of global data analyses, the relationships depicted by these CMR curves represent global mean changes in soil carbon for a given change in land use or land management. In this paper, we describe the development of three CMR curves, how they might be used to account for changes in soil carbon stocks and net greenhouse gas (GHG) emissions, and their effectiveness in addressing some of the policy issues often raised with respect to carbon accounting.

Methods

Development of CMR Curves

Carbon management response curves are representations of the average annual change in soil carbon following changes in land management, and they can also be used to show the cumulative change in soil carbon over time. The CMR curves are developed by using published reviews and analytical data that quantify changes in soil carbon in response to changes in land use and management. In some cases, there are large gaps in time series data, and we have used interpolation and synthesis of existing data or anecdotal evidence to fill out the path of carbon change over time.

The development of each CMR curve is based on analysis of one or more data sets, each describing a number of long-term, paired field experiments. The difference in soil carbon between the control and experimental plot for each field experiment in the data set is averaged across all experiments to estimate the mean change in soil carbon associated with a specific change in management. When possible, the change in soil carbon over time is estimated by plotting the change in soil carbon (with respect to the experimental control) versus the time following the initial change in management (see, for example, Paustian and others 1997, Davidson and Ackerman 1993, Polglase and others 2000, West and Post 2002). Carbon Management Response curves are developed by choosing a regression algorithm that best represents the estimated trend in soil carbon change over time, while ensuring that the sum of annual changes in soil carbon is equal to the previously estimated cumulative change in soil carbon.

Changes in bulk density are expected to occur following changes in land use and management with accumulations or loss of soil organic carbon. While some reviews and analyses used in this study account for changes in soil bulk density, many do not. Since bulk density corrections were not available in all literature reviews and analyses, corrections for bulk density were not included in the current development of CMR curves. Inclusion of bulk density corrections will be considered in the future development of CMR curves.

We developed CMR curves based on the relative (%) change in soil carbon with respect to an initial carbon value or reference point, instead of the absolute change in carbon. Hence, the curves can be applied over different climatic regions that would be expected to have different initial and final carbon values. In order to provide an estimate of the uncertainty surrounding mean changes in soil carbon, 95% confidence intervals were calculated for each CMR curve. We use these 95% confidence intervals for sequestration means, but provide standard error (SE) and sample size (n) so that other confidence intervals can be calculated.

Multiple curves or curve segments can be used consecutively over time to estimate changes in soil carbon that follow several successive changes in land management. When the curves are used in this manner, the percentage rates of carbon change are normalized to the initial soil carbon under the original land cover, referred to hereinafter as the reference point. That is, all of the curve segments will have the same denominator in estimates of percentage change in carbon, and annual increments can be added or subtracted. Curve segments can, therefore, be connected in series to represent a continuous sequence of change in land management.

Full Greenhouse Gas Accounting

In many cases, changes in land use or land management result in changes in CO_2, N_2O, or CH_4 emissions beyond those associated with carbon sequestration. For example, a change from conventional tillage (CT) to no-till (NT) generally results in carbon sequestration, but it also reduces the use of agricultural field machinery, which subsequently reduces the use of fossil fuels and associated CO_2 emissions. A complete analysis of the effect of greenhouse gas mitigation activities should include consideration of these changes. In our use of CMR curves in greenhouse gas accounting, we use CO_2 emissions from agricultural inputs based on estimates from West and Marland (2002).

Emissions of N_2O are expected to increase with increased use of N fertilizers (Food and Agriculture Organization 2001). N_2O emissions may also change with changes in soil management (Mummey and others 1998, Smith and others 2001). Emissions of N_2O can be expressed in C-equivalent (C_{eq}) terms based on the global warming potential of N_2O in comparison with CO_2. Marland and others (2003) estimated that 2.66 kg C_{eq} ha^{-1} is emitted per kilogram of applied synthetic N. This estimate was based on: (1) a global warming potential for N_2O of 310 (the value for CO_2 is 1.0; Houghton and others 1996), (2) an average 1.25% of applied N emitted directly as N_2O (Bouwman 1994), and (3) an additional 0.75% of applied N emitted as N_2O from leaching and volatilization as NO_x and NH_3 (Mosier and others 1996, 1998).

In this study, we use a revised estimate of 2.22 kg C_{eq} per kg synthetic N applied. This is based on revised values: (1) a global warming potential for N_2O of 296 (Houghton and others 2001), (2) an average of 1.0% of applied N emitted directly as N_2O (Food and Agriculture Organization 2001), and (3) an additional 0.126% of applied N emitted as N_2O from volatilization as NO_x and NH_3 (Food and Agriculture Organization 2001) and 0.75% of applied N emitted as N_2O from leaching (Penman and others 2000). We do not consider fluxes of CH_4 in this study.

Results

In this paper, we present CMR curves for three circumstances that involve a change in land use or management with an accompanying change in soil carbon: (a) carbon loss following conversion from forest to agriculture, (b) carbon accumulation following elimination of tillage on croplands, and (c) carbon accumulation following reforestation of agricultural land. Other curves are being developed to characterize additional changes in land management (see Table 1), but these three scenarios, described below, are sufficient to illustrate the development of CMR curves and their use in addressing carbon accounting issues. The CMR curves presented here apply to the top 30 cm of soil.

Soil Carbon Loss Following Conversion from Forest to Agriculture

Loss of soil carbon following clearing and cultivation of forest or grassland soils is caused by the physical disruption of soil aggregates and the subsequent exposure of organic carbon, which is then oxidized and lost as CO_2 to the atmosphere. Loss of carbon can also occur if there is a reduction in plant residue inputs to the soil after cultivation. If cultivation persists, soil carbon will generally continue to decrease until it reaches a new steady state between inputs and outputs. There are a large number of studies that have examined the loss of soil carbon after initial cultivation. Many of these studies are summarized in the analyses discussed below.

In an analysis of carbon flux to the atmosphere, Houghton (1999) estimated a 25%–30% loss of soil carbon (to a 1-meter depth) after clearing of forested land. This loss is expected to occur over 15–50 years, depending on ecosystem type (Houghton and Hackler 2001). Schlesinger (1986) estimated a mean 30% loss of soil carbon over a 20- to 50-year period after forest clearing. In tropical forest soils, Detwiler (1986) estimated that 40% of soil carbon would be lost within the first 5 years when forest is cleared for agriculture. Detwiler (1986) estimated smaller losses of carbon when the forest was cleared for shifting cultivation (18%–27%) and for pasture (20%).

Mann (1986) analyzed 625 paired soil samples and concluded that soils relatively high in carbon may lose up to 20% soil carbon following cultivation of previously uncultivated land, and that the greatest change in soil carbon occurred in the first 20 yr. Soils relatively low in carbon could potentially accumulate carbon after cultivation. Post and Mann (1990) increased the number of paired treatments in the original analysis by Mann (1986), using data from the U.S. Department of Agriculture, Natural Resources Conservation Service. Data from 800 soil profiles were used to estimate soil carbon in cultivated and uncultivated soils for 120 soil series representing major agricultural soils in the U.S. Post and Mann (1990) confirmed that soils high in carbon tended to lose the largest amounts of carbon when cultivated, while soils low in carbon on average showed gains in soil carbon when cultivated. The estimated maximum loss following cultivation of soils was 29% for 0–15 cm depth, 22% for 0–30 cm, and 23% for 0–100 cm.

Davidson and Ackerman (1993) used a data set of 56 paired samples to estimate the loss of soil carbon after cultivation. Their results were reported with respect to both soil horizon and soil depth. A loss of approximately 42.7% ± 5.7% was found for the A horizon, 30.0% ± 5.9% loss for the A and B horizons, and 27.2% ± 2.9% average loss for all depths, including soils sampled to greater than 30 cm depth. A plot of the mean rate of soil carbon loss versus time indicated approximately 20% loss of soil carbon in the first 5 yr after initial cultivation and another 5% in the next 15 yr. Unlike the analyses by Mann (1986) and Post and Mann (1990), Davidson and Ackerman (1993) did not observe a relationship between the amount of carbon loss and the initial amount of soil carbon.

Murty and others (2002) found a 30.3% loss in soil carbon after 10 or more years of cultivation, resembling estimates from Davidson and Ackerman (1993) and Schlesinger (1986). When analyzing only those studies that had been corrected for changes in bulk density, the estimated loss was 22.1% ± 4.1%, similar to estimates of soil carbon loss for the 0– to 30-cm depth by Mann (1986) and Post and Mann (1990). Murty and others (2002) also estimated soil carbon loss for conversion of forest to pasture and found no statistically significant loss of soil carbon.

In developing a CMR curve representing cultivation of previously forested lands, we started with the Murty and others (2002) estimate of 30% ± 4% (SE = 2, n = 75) for carbon loss after cultivation. This estimate tends to reflect the mean results from previous analyses. We note that both Murty and others (2002) and Post and Mann (1990) suggest that the actual loss of soil carbon might be somewhat lower if all of the data were properly adjusted for changes in soil bulk density. The 30% mean cumulative loss in soil carbon is represented in the CMR curve by a double exponential decay function that describes a 25% loss in the first 5 years following cultivation and an additional 5% loss in the subsequent 15 years (Figure 1). This pattern of carbon loss over time is similar to that suggested by Davidson and Ackerman (1993). Combining an estimate of cumulative

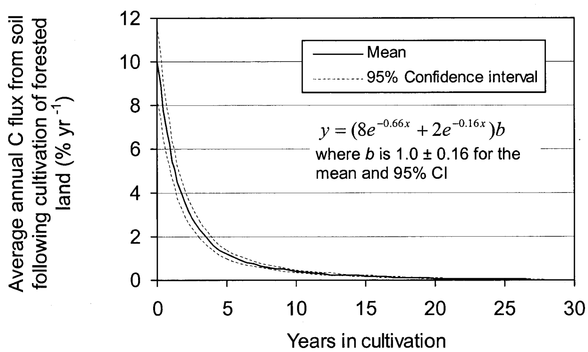

Figure 1. Estimated average annual carbon flux from soil to the atmosphere after clearing and cultivation of forested land.

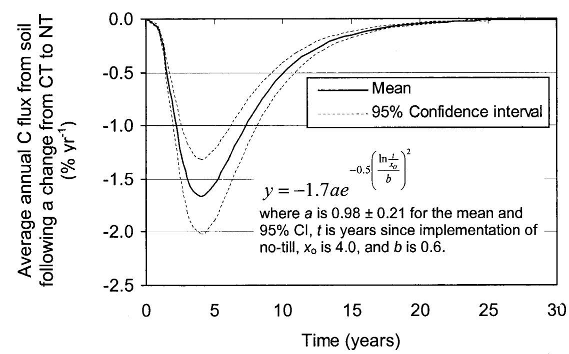

Figure 2. Estimated average annual carbon flux from soil to the atmosphere after a change from conventional tillage (CT) to no-till (NT) on agricultural cropland.

soil carbon loss with the expected pattern in soil carbon loss over time provides annual rates of soil carbon loss.

Soil Carbon Accumulation after Elimination of Tillage

In an analysis of long-term agricultural experiments, West and Post (2002) estimated carbon sequestration rates for different crop sequences with a change from CT to NT on croplands. A mean increase in soil carbon of 16.3% ± 3.5% (SE = 1.75, n = 79) was estimated for all cropping systems, excluding wheat-fallow rotations. If we assume that the soil carbon content of the original forested land was reduced to 70% of its initial value as a result of cultivation, the subsequent conversion to NT would thus result in restoration to 81.4% of its initial value; that is, normalizing the increase in soil carbon to the soil carbon content of the original, forested land; conversion from CT to NT will result in an increase equivalent to 11.4% ± 2.4% of the initial soil carbon stock. The reference point in our computations is the original, forested state.

In a separate analysis, West and Post (2002) analyzed experiments with a chronosequence of soil carbon measurements to estimate the time period over which sequestration occurs after a decrease in tillage intensity, and how annual sequestration rates changed over time. Carbon accumulation was estimated to occur over a 15- to 20-year period, with maximum sequestration rates occurring between 5 and 10 years. Combining estimates of both rates and duration of carbon sequestration, we developed a CMR curve for average accumulation of soil carbon after a change from CT to NT (Figure 2). The CMR curve was constructed using a log normal regression algorithm representing the expected delay in carbon accumulation in the early years, with maximum accumulation rates occurring between years 5 and 10.

Soil Carbon Accumulation after Reforestation of Agricultural Land

Rates of soil carbon accumulation will depend not only on environmental variables and weather conditions, but also on land-use history. In the case of reforestation after cultivation, the duration and intensity of historical cultivation will determine how much soil carbon has been lost and consequently how much may be regained. In an analysis of carbon accumulation following a change from agricultural land to forest, Post and Kwon (2000) estimated an average increase in soil carbon of about 33.8 g C m^{-2} y^{-1}. Using an approach similar to that used by Post and Kwon (2000) for estimating soil bulk density and changes in the mass of soil carbon, Paul and others (2002) estimated an increase of 30.2 g C m^{-2} y^{-1} after reforestation of agricultural lands. The percentage change in soil carbon for reforestation of agricultural land (for 0- to 30-cm depth) was estimated at 0.56% yr^{-1} (Paul and others 2002, Polglase and others 2000). An analysis of the percentage change in soil carbon over time suggests that a new steady state is reached in approximately 40–60 years after reforestation (Polglase and others 2000). This estimated time to reach a new steady state after reforestation is similar to that illustrated by Silver and others (2000) for tropical ecosystems. Using the estimate of 0.56% C yr^{-1} (Paul and others 2002, Polglase and others 2000) over a 60-year period, along with the standard error and sample size associated with the estimated change in soil carbon stock (30.2 ± 28.38 g C m^{-2} y^{-1}, SE = 13.9, n = 33), results in an estimate of about a 34% ± 32% increase in soil carbon.

Results from Paul and others (2002) and Polglase and others (2000) indicate that a loss of soil carbon can occur during the first 5 years after reforestation, after which soil carbon recovers and surpasses the amount present under agricultural management. Silver and

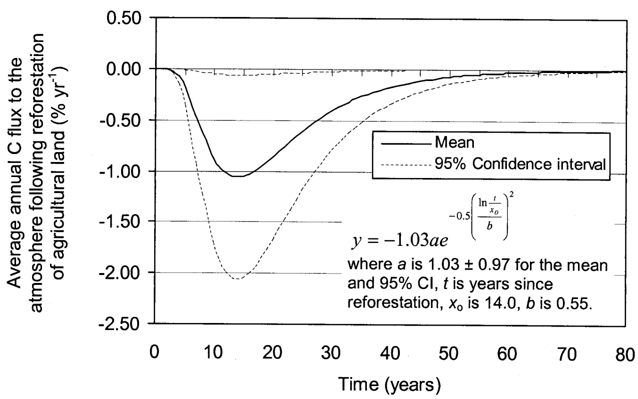

Figure 3. Estimated average annual C flux from soil to the atmosphere after abandonment and reforestation of agricultural land.

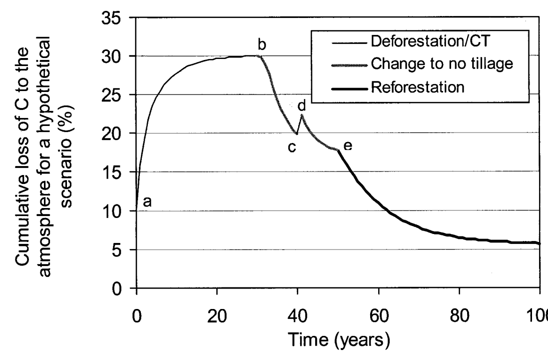

Figure 4. Cumulative loss of carbon from soil to the atmosphere estimated for a hypothetical land management scenario (see text). Hypothetical scenario consists of (a) deforestation and cultivation of soil using conventional tillage, (b) changing from conventional tillage to no-till, (c) use of conventional tillage for one year, (d) returning to the use of no-till, and (e) abandoning the land and allowing forest conditions to re-establish.

others (2000) indicate that the greatest accumulation rates occur in the first 20 years (130 g m^{-2} yr^{-1}) with lower rates in the subsequent 80 years of carbon accumulation (20 g m^{-2} yr^{-1}). Combining these trends of carbon accumulation over time, we expect to see a log normal distribution of carbon accumulation rates (similar to that for a change from CT to NT in Figure 2), over a 60-year period, with maximum accumulation rates occurring between years 10 and 20 (Figure 3). The 34% increase in soil carbon after reforestation presumably follows a drop to 70% of the initial value that occurred when forest land was originally cultivated. Thus reforestation can be expected to return soil carbon to 94% of its initial value. That is, the 34% increase in soil carbon represents an increase equivalent to 24% of the amount of carbon initially held in the soil prior to disturbance. The wider confidence interval surrounding the mean change in soil carbon for reforestation (Figure 3) is due both to a higher standard error and to a sample size that is less than half that used in development of the previously discussed CMR curves. Confidence intervals for all estimates and CMR curves are expected to narrow as more data become available.

Application of CMR Curves

Estimating Changes in Soil Carbon Following Multiple Changes in Land Management

Use of CMR curves enables estimates of soil carbon after a series of changes in land management. Annual changes in soil carbon can be estimated by moving between curves that represent different changes in land management. To exemplify this, we use a hypothetical scenario beginning with a primary forest at year 0 that is converted to CT agriculture for 30 years. No-till practice is then implemented for 10 years, followed by an additional 1 year of CT, and followed by another 9 years of NT. The land is abandoned at year 50 and reverts back to secondary forest. In accounting for changes in soil carbon throughout this scenario, we use the three aforementioned CMR curves representing mean changes in soil carbon from (a) deforestation by using CT, (b) a change from CT to NT, and (c) reforestation. Each time there is a change in land management, estimates of the annual change in soil carbon continue on a different curve. The point where estimates resume on the new curve depends on the amount of carbon that was previously lost or gained with respect to the original land use and the initial carbon stock. With the scenario provided above and the CMR curves in Figures 123, a cumulative change in soil carbon can be estimated (Figure 4). The serial connection of these CMR curves exemplifies how the curves might be used in a carbon accounting system.

Comparison between the CMR curves developed here and a response curve from Houghton and Hackler (2001) (Figure 5), representing a scenario of deforestation and subsequent reforestation, can be made by removing the change in agricultural management (i.e., change from CT to NT) in Figure 4. The CMR curves presented in Figure 5 are a combination of the deforestation and reforestation CMR curves, applied to an initial soil carbon value of 55,000 kg ha^{-1} per 30-cm depth. This initial carbon value is generally representative of Alfisols and Ultisols occurring in the Eastern United States, assuming an initial 1.4% carbon content and a soil bulk density of 1.3 Mg m^{-3}. The response

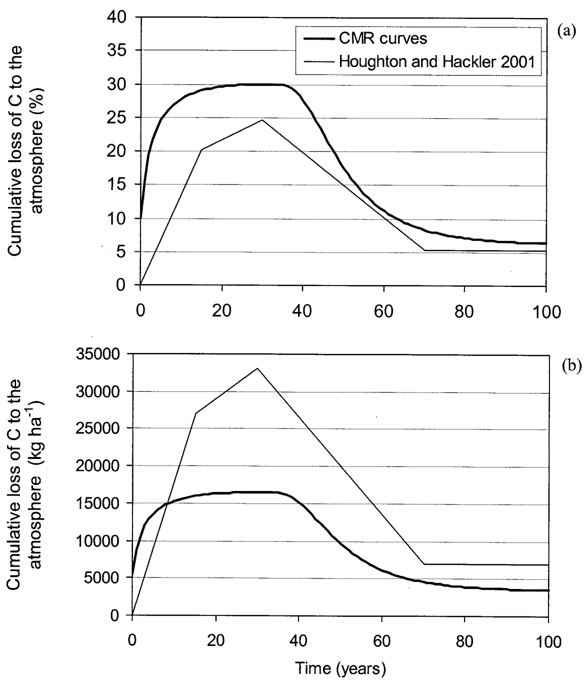

Figure 5. Cumulative loss of carbon from soil to the atmosphere resulting from cultivation of previously forested land for 30 years, followed by reforestation. Parts (a) and (b) show the percentage and absolute change in the soil carbon stock, respectively. The dark trend lines show the use and integration of CMR curves, and the light lines represent estimates from Houghton and Hackler (2001) for comparison.

curve from Houghton and Hackler (2001) is based on a 25% loss of soil carbon for temperate evergreen and deciduous forests in North America, with an initial soil carbon value of 134,000 kg ha^{-1} per 100-cm depth.

The two curves are similar in terms of the percentage net loss of soil carbon to the atmosphere (Figure 5a). Following reforestation, both response curves recover to approximately 95% of original soil carbon. The difference between the two response curves becomes apparent when they are applied to the initial soil carbon values or reference point (Figure 5b). The Houghton and Hackler (2001) response curve represents changes in soil carbon to a 1-m depth. Although some experiments indicate a change occurring in soil carbon to a 1-m depth (Schlesinger 1986), many analyses do not report such changes (Mann 1986, Paul and others 2002, West and Post 2002), owing either to a lack of significant change in lower soil horizons or a lack of available data. The Houghton and Hackler (2001) response curve results in a 17,000 kg C ha^{-1} greater loss of soil carbon after conversion of forest to agriculture than does the CMR curve.

Estimating Changes in Net Greenhouse Gas Emissions to the Atmosphere

Changes in the emissions of greenhouse gases associated with changes in land management can be incorporated into CMR curves. In the example presented here, we consider CO_2 from the combustion of fossil fuels and N_2O emissions from the application of N fertilizers. Emissions of CO_2 associated with agricultural production coincide with that of an average U.S. agricultural crop, as estimated by West and Marland (2002). We again use the land management scenario from Figure 4 and apply the CMR curves to an initial soil carbon value of 55,000 kg C ha^{-1} to a 30-cm depth.

When one considers emissions associated with changes in land management, a loss of about 7000 kg C ha^{-1} occurs in our example scenario even after much of the soil carbon stock is replenished after reforestation (Figure 6a). This loss is due to both soil carbon loss and greenhouse gas emissions associated with agricultural production.

However, many agricultural lands in the U.S. have been using some form of conventional tillage for decades. In these cases, the logical starting point and baseline for greenhouse gas accounting may be cultivated lands using CT practices (Figure 6b), not the initial forest conditions that existed in past decades. With CT as the baseline, greenhouse gas accounting begins at year 30. When NT agriculture is implemented in year 30, soil carbon stocks increase, and CO_2 emissions from the use of farm machinery decrease. Again, there is a slight loss of soil carbon in year 40, during the one additional year of conventional tillage, but soil carbon increases dramatically and emissions cease when the land is reforested in year 50. Since the baseline scenario in Figure 6b is now CT, the savings in emissions due to reforestation occur indefinitely.

Addressing Carbon Accounting Issues with CMR Curves

A number of issues have arisen in attempting to estimate and record changes in carbon stocks in the terrestrial biosphere and, perhaps more importantly, in attempting to estimate changes in net greenhouse gas emissions that accompany changes in land management (see, for example, Watson and others 2000, Schlamadinger and Marland 2000). Specifically, we consider baselines, carbon saturation, permanence of sequestered carbon, uncertainty surrounding estimates of carbon sequestration, and the flexibility and transparency within an accounting system. We discuss how CMR curves can be applied while considering these issues.

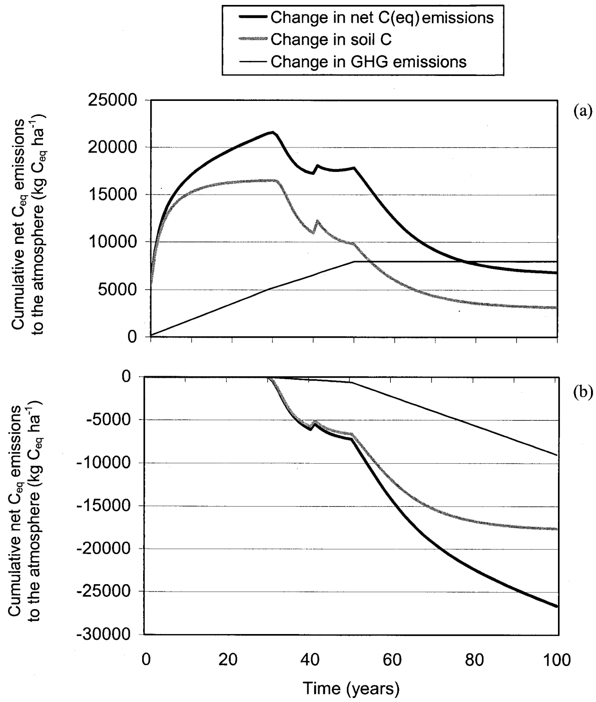

Figure 6. Cumulative change from the point of departure, over time, for soil carbon, greenhouse gas emissions from agriculture, and the sum of these two components. Greenhouse gas emissions from agriculture include CO_2 emissions from fuel use and agricultural inputs and N_2O emissions related to the use of nitrogen fertilizers. Positive values indicate emissions to the atmosphere and are expressed in carbon equivalents. Part (a) shows the cumulative change in net emissions with respect to a baseline of primary forest. Part (b) shows the cumulative change in net emissions with respect to a baseline of conventional tillage. Calculated values for soil carbon are based on the CMR curves and a reference point, which is the carbon content of the primary forest.

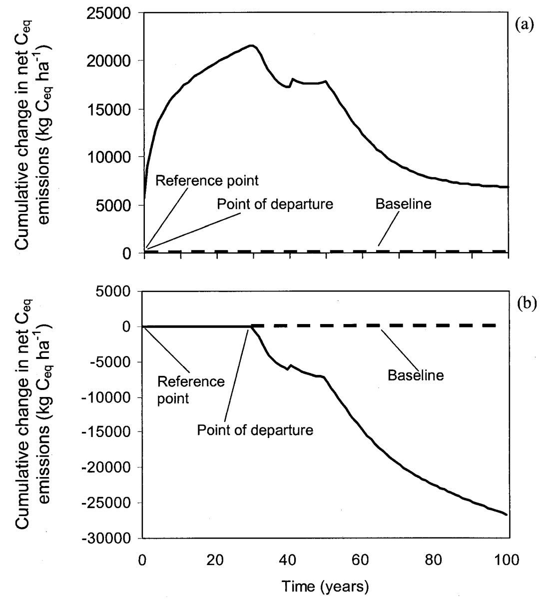

Figure 7. Cumulative change in net C_{eq} emissions to the atmosphere (from Figure 6) relative to (a) a baseline of primary forest and (b) a baseline of conventional tillage. Baselines are trends indicating the business-as-usual scenario and are determined by the point of departure. The reference point represents "natural" ecosystem conditions and determines the potential for soil carbon accumulation or loss associated with serial changes in land management over time.

Baseline and reference point. Establishment of a baseline for carbon accounting is necessary for estimating a change in carbon due to a specific change in land management. For composite CMR curves, like those constructed in Figure 4, we can choose any point on the curve as the starting point to define both the baseline scenario and the departure from the baseline scenario (Figure 7). This starting point, referred to as the "point of departure" hereinafter, is chosen based on where the accounting of soil carbon change is to begin. The point of departure influences the relative amount of soil carbon lost or gained (Figure 6) and the relative change in net C_{eq} emissions to the atmosphere (Figures 6 and 7).

A reference point for carbon accounting, representing the initial soil carbon value, is also necessary. The reference point enables calculation of the absolute change in carbon, by using relative (%) changes provided by the CMR curves and by following the temporal trend in soil carbon change prescribed by the CMR curves. The reference point provides a common denominator for understanding fractional changes through time and for being able to perform arithmetic functions with those fractional values. The reference point in both Figures 7a and 7b is the initial soil carbon value under the "natural" forest conditions, regardless of where the point of departure is placed, and all points on the composite CMR curve represent percentage gains and losses in soil carbon relative to the reference point.

Soil carbon saturation and additionality. In theory, soil carbon will eventually reach saturation based on a balance of carbon inputs and losses; beyond this point, there would be no additional net change in soil carbon if land use and management remain the same. In terms of changing management practices, we expect soil carbon to reach a new steady state some time after implementation of a new practice. We differentiate between this new steady state and soil carbon saturation because soil carbon could potentially increase again following a second change in management. The development of

CMR curves results in estimates of annual rates of change in soil carbon, thereby providing an approximation for when and at what level a steady state in soil carbon will be reached after a change in land management.

The time necessary for soil to reach a new steady state differs depending on the change in land management and the prevailing weather conditions. Since CMR curves are estimates of soil carbon change based on differences between paired experiments, the response of soil carbon to natural variability in the environment should be largely cancelled when calculating the difference in soil carbon between paired measurements. Therefore, the change in soil carbon represented by CMR curves and the time until a new steady state is reached should be due only to changes in land management and not to changes in weather conditions or other environmental factors. In this sense, CMR curves provide an option to satisfy the issue of "additionality". Additionality refers to the requirement that accounted changes in carbon stocks be a direct result of changes in management specifically initiated to sequester additional carbon, as opposed to natural changes in environmental factors that would have occurred otherwise (see, for example, Schlamadinger and Marland 2002, Mooney and others 2002).

The method of developing CMR curves and the use of paired data inherently ensure that the change in carbon represented by the CMR curve is a change additional to what would have occurred if no change in management were initiated. The ability of CMR curves to capture trends depends on the quality and representativeness of the match between the conditions under which the CMR curve was estimated and the conditions for the management change being evaluated. The changes to be expected in soil carbon after a change from CT to NT, for example, may be very different for corn versus wheat (West and Post 2002) or for dry versus wet environments. A CMR curve constructed from data on mid-latitude sites may provide little insight on changes in soil carbon in the tropics or how these changes will be affected by variability in the natural environment. The more specific and narrowly focused the data for constructing a CMR curve, the more likely it is to provide an appropriate estimate of changes in soil carbon due to a specific change in management.

Permanence of sequestered carbon. Permanence of sequestered carbon refers to the length of time that carbon, once sequestered, remains sequestered. For example, if a ton of carbon is not emitted from the combustion of fossil fuel in any given year, then it is assumed to be permanently saved from the atmosphere. If a ton of carbon is sequestered in soil and therefore not released to the atmosphere, it might be considered temporary, since it can still be released in the future. CMR curves can represent either the accumulation or release of carbon, and can thus estimate either the credits that accrue as carbon stocks are increased or the debits that accumulate as carbon stocks are drawn down. However, since CMR curves are intended to represent the mean temporal path of changes in carbon stocks, they do not exhibit the annual variability in carbon stocks that commonly occur in the field. CMR curves smooth out any annual variability that might produce an alteration of credits and debits or an irregular flow of credits due to natural variability. They do, however, show reversals in management practices, such as the one-year return to conventional tillage illustrated in Figure 4.

Uncertainty in sequestration estimates. Estimates of uncertainty surrounding mean changes in soil carbon can be included in CMR curves because the curves are statistically based on multiple, paired field experiments. In most cases, the standard error and sample size are provided with the field data used to develop the CMR curves. Of course, the uncertainty will be reduced as CMR curves are based on larger sample sizes and on experiments that are more directly representative of the regions and ecosystems of interest. CMR curves represent only the change in soil carbon and the error surrounding this change. There will also be a measure of error surrounding the initial soil carbon stock, and this should be considered when applying CMR curves to initial soil carbon values.

The degree of acceptable uncertainty is ultimately a policy decision. The suggestion has been offered, for example, that sequestration projects could receive credit, not for the mean amount of carbon sequestered, but for some statistical derivative from the mean, perhaps the mean less one standard deviation (Canada 1998). This kind of calculation could easily be incorporated within CMR curves. Similarly, it would be possible to devise schemes whereby the incentive for sequestration would be weighted in proportion to the uncertainty of the sequestration estimate. Regardless of the accounting framework chosen, the uncertainty associated with CMR curves can provide a basis for informed policy decisions.

Flexibility and transparency within an accounting system. Flexibility and transparency are subjective terms that can be considered only in a comparative manner with other proposed systems, and yet they describe important features of a carbon accounting system. Flexibility refers to the accounting system's ability to respond to changes in carbon dynamics. This may be changes in soil carbon associated with both planned and unplanned changes in land use and management. The use of CMR curves and the ability to move between and combine curve segments should provide sufficient flexibility in responding to changes in land use and management.

Transparency refers to the ability of an informed observer to understand the system with a reasonable amount of effort and in a reasonable amount of time. The CMR curves are straightforward in that they are relatively simple mathematical equations based on empirical data that represent changes in soil carbon resulting from changes in land use and management. Carbon accumulation and loss rates, used in the development of CMR curves, may be coarse in their ability to represent changes in carbon at the field to regional scales, but they are more transparent than process-based models. There are, of course, trade-offs between the two approaches in that process-based models, while less transparent, may be able to account for additional, site-specific variables that may diminish or augment average expected changes in carbon stocks. Estimated changes in carbon stocks using CMR curves will be direct, predictable, and transparent responses to management decisions.

Discussion and Conclusion

The CMR curves presented here are estimates of changes in carbon stocks as a function of changes in land use and land management. The curves are a result of global data compilation and analysis. They differ from traditional, non-temporal estimates in that they incorporate changes in the annual rates of carbon accumulation or loss over time, while estimating the time to peak rates of change and the time to reach a new carbon steady state. This paper has focused on soil carbon, but CMR curves could be generated for above- and below-ground changes in terrestrial carbon. Additional stratification of the data could result in region-specific CMR curves, depending on data availability.

Carbon management response curves represent mean changes in soil carbon with changes in land use or management. Data from the analyses used to generate the curves indicate that in many cases there are both increases and decreases associated with the same changes in management. Differences in measured soil carbon changes may be due to differences in land use history or may be due to other environmental factors not yet understood. As more information becomes available, correction factors could be included with CMR curves to represent effects of other regional or site-specific environmental variables.

The review of existing analyses during the development of CMR curves can be used to verify that the results of existing analyses are consistent. For example, if the results from existing analyses are consistent, carbon losses described in one global analysis, such as for conversion from forest to agriculture, ought to roughly counterbalance carbon gains for a reversal in management activity described in a separate global analysis, such as reforestation of agricultural land. The results of all analyses should, in theory, function together and be compatible with our basic knowledge of ecological dynamics. In attempting to combine quantitative analyses to form a comprehensive picture of carbon dynamics and a functional system for carbon accounting, it is evident that the methodologies and the presentation of results differ greatly between analyses. Eventually, all experimental data should be brought together in a single database for re-analysis, and results should reflect the information that is needed from a policy perspective.

Carbon management response curves offer a method for estimating changes in carbon stocks over time in response to changes in land use and management. Consideration should be given to the use of CMR curves in carbon accounting frameworks because of their simplicity and ability to effectively address a number of carbon accounting issues discussed earlier in this paper. The curves may also be useful for developing or validating biogeochemical models or for providing both new and revised mathematical relationships that represent the effects of land use and management on terrestrial carbon stocks.

Acknowledgements

The research was performed as part of the Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSITE) and as part of the Integrated Assessment Program, both sponsored by the U.S. Department of Energy's Office of Science, Biological and Environmental Research. We are indebted to Siân Mooney, Stephen M. Ogle, and Charles T. Garten for helpful comments on an earlier version of this paper. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the U.S. Dept. of Energy under contract DE-AC05-00OR22725.

References

Bouwman, A. F. 1994. Direct emissions of nitrous oxide from agricultural soils. RIVM report No. 773004004. National Institute of Public Health and the Environment, Bilthoven, the Netherlands.

Canada. 1998. Methodological Issues, Inventories, and Uncertainties. Paper No. 1. UNFCCC, Subsidiary Body for Scientific and Technological Advice. [Available at http://unfccc.int/resource/docs/1998/sbsta/misc06a01.pdf].

Conant, R. T., K. Paustian, and E. T. Elliott. 2001. Grassland management and conversion into grassland: effects on soil carbon. *Ecological Applications* 11:343–355.

Davidson, E. A., and I. L. Ackerman. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry* 20:161–193.

Detwiler, R. P. 1986. Land use change and the global carbon cycle: the role of tropical soils. *Biogeochemistry* 2:67–93.

Food and Agriculture Organization. 2001. *Global estimates of gaseous emissions of NH_3, NO, and N_2O from agricultural land.* International Fertilizer Industry Association, FAO, Rome, Italy, 106 pp.

Heath, L. S., J. M. Kimble, R. A. Birdsey, and R. Lal. 2003. The potential of U.S. forest soils to sequester carbon. . Pages 385–392 *in* J. M. Kimble, L. S. Heath, R. A. Birdsey, and R. Lal. Eds, The potential for U.S. forest soils to sequester carbon and mitigate the greenhouse effect. CRC Press, New York.

Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell. 1996. Climate Change 1995—The Science of Climate Change. Cambridge University Press, New York.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson. 2001. Climate Change 2001: The Scientific Basis. Cambridge University Press, New York.

Houghton, R. A., R. D. Boone, J. R. Fruci, J. E. Hobbie, J. M. Melillo, C. A. Palm, B. J. Peterson, G. R. Shaver, and G. M. Woodwell. 1987. The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: geographic distribution of the global flux. *Tellus* 39B:122–139.

Houghton, R. A.and Hackler, J. L. 2001. *Carbon flux to the atmosphere from land-use changes: 1850–1990.* ORNL/CDIAC-131, NDP-050/R1. Carbon Dioxide Information Analysis Center, U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A. 86pp. [Available at http://cdiac.esd.ornl.gov/epubs/ndp/ndp050/ndp050.html]

Houghton, R. A., J. E. Hobbie, J. M. Melillo, B. Moore, B. J. Peterson, G. R. Shaver, and G. M. Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere. *Ecological Monographs* 53:235–262.

Houghton, R. A. 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus* 51B:298–313.

Mann, L. K. 1986. Changes in soil carbon storage after cultivation. *Soil Science* 142:279–288.

Marland, G., T. O. West, B. Schlamadinger, and L. Canella. 2003. Managing soil organic carbon in agriculture: the net effect on greenhouse gas emissions. *Tellus* 55B:613–622.

Mooney, S., Antle, J., Capalbo, S. and Paustian, K. (2002) Contracting for soil carbon credits: design and costs of measurement and monitoring. Staff Paper 2002-01, Department of Agricultural Economics and Economics, Montana State University, Boseman, Montana. [Available at http://www.climate.montana.edu/pdf/mooney.pdf].

Mosier, A. R., J. M. Duxbury, J. R. Freney, O. Heinemeyer, and K. Minami. 1996. Nitrous oxide emissions from agricultural fields: assessment, measurement and mitigation. *Plant and Soil* 181:95–108.

Mosier, A. R., J. M. Duxbury, J. R. Freney, O. Heinemeyer, and K. Minami. 1998. Assessing and mitigating N_2O emissions from agricultural soils. *Climatic Change* 40:7–38.

Mummey, D. L., J. L. Smith, and G. Bluhm. 1998. Assessment of alternative soil management practices on N_2O emissions from US agriculture. *Agriculture, Ecosystems and Environment* 70:79–87.

Murty, D., M. U. F. Kirschbaum, R. E. McMurtie, and H. McGilvray. 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Global Change Biology* 8:105–123.

Paul, K. I., P. O. Polglase, J. G. Nyakuengama, and P. K. Khanna. 2002. Change in soil carbon following afforestation. *Forest Ecology and Management* 168:241–257.

Paustian, K., O. Andrén, H. H. Janzen, R. Lal, P. Smith, G. Tian, H. Tiessen, M. Van Noordwijk, and P. C. Woomer. 1997. Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management* 13:230–244.

Penman, J., Kruger D., Galbally, I., Hiraishi, G., Nyenzi, B., Emmanuel, S., Buendia, L., Hoppaus, R., Martinsen, T., Meijer, J., Miwa, K., Tanabe, K. (eds.) (2000) *Good practice guidance and uncertainty management in national greenhouse gas inventories.* Institute for Global Environmental Strategies, Kanagawa, Japan.

Polglase, P. J., K. I. Paul, P. K. Khanna, J. G. Nyakuengama, A. M. O'Connell, T. S. Grove, and M. Battaglia. 2000. Change in soil carbon following afforestation or reforestation. Technical report no. 20. Australian Greenhouse Office, Canberra, Australia.

Post, W. M. 2003. Impact of soil restoration, management, and land-use history on forest-soil carbon. Pages 191–199 *in* J. M. Kimble, L. S. Heath, R. A. Birdsey, and R. Lal. Eds, The potential for U.S. forest soils to sequester carbon and mitigate the greenhouse effect. CRC Press, New York.

Post, W. M., and K. C. Kwon. 2000. Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology* 6:317–327.

Post, W. M., and L. K. Mann. 1990. Changes in soil organic carbon and nitrogen as a result of cultivation. Pages 401–406 *in* A. F. Bouwman Eds, Soils and the Greenhouse Effect. John Wiley & Sons, New York.

Schlamadinger, B., and Marland, G. (2000) *Land use and global climate change—forests, land management, and the Kyoto Protocol.* Pew Center on Global Climate Change, Arlington, Virginia.

Schlesinger, W. H. 1986. Changes in soil carbon storage and associated properties with disturbance and recovery. Pages 194–220 *in* J. R. Trabalka, and D. E. Reichle. Eds, The changing carbon cycle-a global analysis. Springer-Verlag, New York.

Silver, W. L., R. Ostertag, and A. E. Lugo. 2000. The potential for carbon sequestration through reforestation of abandoned tropical agricultural and pasture lands. *Restoration Ecology* 8:394–407.

Smith, P., K. W. Goulding, K. A. Smith, D. S. Powlson, J. U. Smith, P. Falloon, and K. Coleman. 2001. Enhancing the carbon sink in European agricultural soils: including trace gas fluxes in estimates of carbon mitigation potential. *Nutrient Cycling in Agroecosystems* 60:237–252.

Watson, R. T., I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo, and D. J. Dokken. 2000. Land use, land-use change, and forestry. Intergovernmental Panel on Climate Change special report. Cambridge University, New York.

West, T.O. 2002. Soil carbon accounting: options to measure, monitor, and address project-level issues. Forestry and Agriculture Greenhouse Gas Modeling Forum. Shepherdstown, West Virginia: 8–11 October, 2002. [Available at http://foragforum.rti.org/documents/West.ppt]

West, T. O., and G. Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. *Agriculture, Ecosystems and Environment* 91:217–232.

West, T. O., and W. M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Science Society of America Journal* 66:1930–1946.

Whiting, G. J., and J. P. Chanton. 2001. Greenhouse carbon balance of wetlands: methane emissions versus carbon sequestration. *Tellus* 53B:521–528.