

Net carbon flux from agricultural ecosystems: methodology for full carbon cycle analyses

T.O. West*, G. Marland

Environmental Sciences Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831-6335, USA

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“Capsule”: *A methodology was used for analysis that accounts for changes in carbon sequestration, carbon emissions, and net carbon flux with time.*

Abstract

Agricultural ecosystems have the potential to sequester carbon in soils by altering agricultural management practices (i.e. tillage practice, cover crops, and crop rotation) and using agricultural inputs (i.e. fertilizers and irrigation) more efficiently. Changes in agricultural practices can also cause changes in CO₂ emissions associated with these practices. In order to account for changes in net CO₂ emissions, and thereby estimate the overall impact of carbon sequestration initiatives on the atmospheric CO₂ pool, we use a methodology for full carbon cycle analysis of agricultural ecosystems. The analysis accounts for changes in carbon sequestration and emission rates with time, and results in values representing a change in net carbon flux. Comparison among values of net carbon flux for two or more systems, using the initial system as a baseline value, results in a value for relative net carbon flux. Some results from using the full carbon cycle methodology, along with US national average values for agricultural inputs, indicate that the net carbon flux averaged over all crops following conversion from conventional tillage to no-till is $-189 \text{ kg C ha}^{-1} \text{ year}^{-1}$ (a negative value indicates net transfer of carbon from the atmosphere). The relative net carbon flux, using conventional tillage as the baseline, is $-371 \text{ kg C ha}^{-1} \text{ year}^{-1}$, which represents the total atmospheric CO₂ reduction caused by changing tillage practices. The methodology used here illustrates the importance of (1) delineating system boundaries, (2) including CO₂ emissions associated with sequestration initiatives in the accounting process, and (3) comparing the new management practices associated with sequestration initiatives with the original management practices to obtain the true impact of sequestration projects on the atmospheric CO₂ pool. Published by Elsevier Science Ltd.

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1. Introduction

The rising atmospheric carbon dioxide (CO₂) concentration, believed to be the primary cause of global climate change, has encouraged proposals to both reduce human-induced CO₂ emissions and sequester carbon (C) in the Earth's biosphere. Carbon sequestration is the increase of carbon in long-term terrestrial or aquatic C stocks, thereby reducing the atmospheric CO₂ concentration. There is general agreement that many agricultural ecosystems have the potential to support

enhanced carbon sequestration in the soil (Watson et al., 2000). Carbon transfer to the soil occurs due to photosynthetic plant growth and the subsequent decomposition of plant material, of which a portion becomes incorporated within the soil.

Anthropogenic disturbances of both natural and managed ecosystems can cause changes in ecosystem structure and function, and can potentially alter biogeochemical cycling and the overall sustainability of ecosystems (Wali et al., 1999). Similarly, altering the management of agricultural ecosystems can result in changes in carbon fluxes, including changes in soil organic carbon (SOC) and CO₂ emissions associated with agricultural practices (Paustian et al., 2000; West and Marland, 2001). Optimizing agricultural management through efficient use of fertilizers, irrigation, and tillage operations can often enhance C sequestration while simultaneously

* Corresponding author. Tel.: +1-865-574-7322; fax: +1-865-574-2232.

E-mail address: westto@ornl.gov (T.O. West).

reducing the C emissions associated with agricultural inputs such as fertilizers and on-farm fuels.

In attempts to quantify the potential for C sequestration in agricultural ecosystems that would accompany changes in agricultural practices, the change in C emissions associated with agricultural practices has largely been overlooked. While some efforts have been made to include emissions as a part of large-scale analyses of C sequestration (e.g. Kern and Johnson, 1993), the lack of readily available and comprehensive emissions data for agricultural fuel use and other activities has made such efforts difficult. Additionally, the lack of a consistent approach to account for agricultural emissions has caused disagreement as to whether the change in C emissions resulting from a change in tillage practice counter-balances the amount of C sequestered in soil (Schlesinger, 1999; Izauralde et al., 2000).

We have used a systematic approach for C accounting of agricultural ecosystems. Examples of a full C cycle analysis are given here for agricultural lands that have converted from conventional tillage to no-till. We draw comparisons between agricultural management options to illustrate which practices result in the least amount of net C flux to the atmosphere. The term “conventional tillage” is used in our analysis for tillage operations that include the use of a moldboard plow, while “no-till” management leaves the soil relatively undisturbed. Data are based on average practice in the United States.

2. Materials and methods

2.1. System dynamics

While C sequestration initiatives in agriculture can have many benefits, e.g. decreased soil erosion, increased soil tilth, and increased water-holding capacity, the current focus on C sequestration in soils is primarily in regard to reducing the atmospheric CO₂ pool and mitigating C emissions from fossil fuel combustion. Since the ultimate goal is a reduction in atmospheric CO₂, our accounting methods result in estimates of net C flux to the atmosphere. In order to attain a value of net C flux that represents the true impact on the atmospheric CO₂ pool, consideration is given to both C sequestered in the ecosystem and C emissions from agricultural inputs.

Calculating C sequestration and C emissions, and hence the total C flow in and out of the system, is based on the same methods of systems ecology outlined by Odum (1983). As in all ecosystem analyses, boundaries of the ecosystem being studied are established (Fig. 1) and all factors that significantly impact the subject of interest are included. In this case, the subject of primary interest is atmospheric CO₂. Because the focus here is on atmospheric CO₂, flows of CO₂ to the atmosphere

are shown as positive whereas flows out of the atmosphere are negative. For combustion of fossil fuels, the flows of CO₂ are recorded. For biological pools, the change in C stocks are recorded and the sum of flows into and out of the stock are considered equal to the change in the stock (Fig. 1). In keeping with definitions suggested by the Intergovernmental Panel on Climate Change (Watson et al., 2000), sequestration is an increase in the C stock of a pool other than the atmosphere.

In agriculture, CO₂ is released by (1) decomposition of crop residues and SOC, which is enhanced by intensive tillage practices, (2) production and application of crop inputs, (3) direct use of fossil fuels in farm machinery, and (4) burning or other oxidation of biomass. The only process of CO₂ uptake is photosynthesis and the only pool in which C can be sequestered is the soil. The amount of C lost via harvested crops is considered to be replaced by C uptake in the following crop and there is no significant long-term accumulation of C in crops or crop products. While CO₂ efflux from soil is expected to be affected by changes in tillage management (Aslam et al., 2000), the loss of this C is inherently accounted for in the changes of SOC.

Based on our definition of the system boundary and the carbon stocks and flows, a full C cycle analysis includes (1) the rate of C sequestration in the soil and

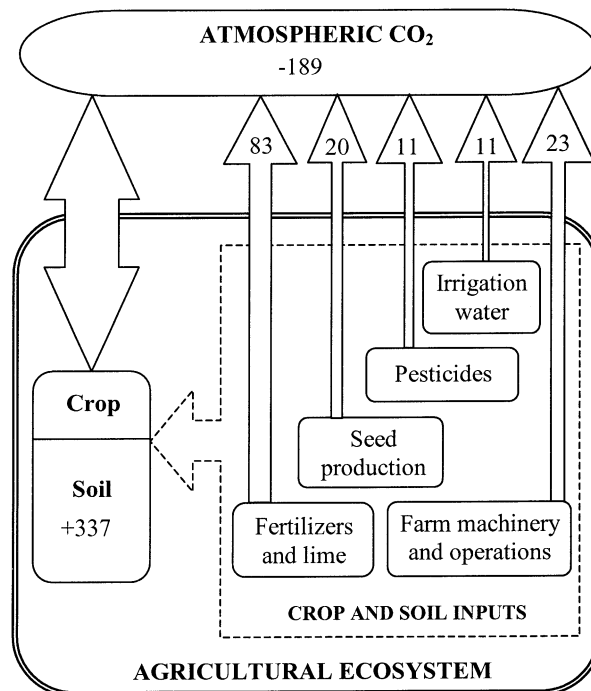


Fig. 1. Annual carbon flux in agricultural ecosystems for the early years following a change from conventional tillage to no-till, based on average US crop inputs. Values embedded in arrows measure rates of flow; other values measure changes in stocks. Rates of flow between the atmosphere and biosphere (crop/soil pool) are inherent in the change in soil carbon stock. Units in kg C ha⁻¹ year⁻¹. Based on data in West and Marland (2001).

(2) the rate of C emissions attributed to management activities. These can be used to derive: (3) the net exchange of C with the atmosphere; (4) the temporal path of C changes, i.e. to follow changes in net C flux with time; and (5) a comparison of relative C flux, i.e. to clarify the differences among two or more management practices.

Accounting for C emissions associated with agricultural operations, in addition to changes in soil C, results in a value of absolute net C flux (hereafter referred to as “net C flux”; Eq. (1). Net C flux indicates whether a system is a net sink (negative values) or a net source (positive values) for atmospheric CO₂.

Absolute net C flux = C emissions

$$- \text{C sequestration} \quad (1)$$

It is, of course, the relative values of net C flux for two systems that indicate their relative benefit with respect to atmospheric CO₂ (Eq. 2). Relative net C flux uses the original system (conventional tillage practice in this case) as the baseline measurement by subtracting values for the baseline from the respective values for the new system (no-till practice).

Relative net C flux = Net C flux_{system 2}

$$- \text{Net C flux}_{\text{system 1}} \quad (2)$$

Following a change in agricultural practice there is likely to be a change in various C flows. With continuation of the new practice one can expect a gradual approach to a new steady state as the C stocks and flows adjust to the new management regime, i.e. C sequestration or C losses from the soil should approach zero with time. On the other hand, C emissions associated with the new practice will continue indefinitely, or until another alternative practice is implemented. The cumulative relative net C flux (Eq. 3) measures the integral (sum) of relative net C flux over time. Summing the annual accumulations of soil C provides a value for the total C sequestered and indicates the amount of time that the accumulated soil C can offset emissions.

Cumulative relative net C flux

$$= \int_0^t (\text{Net C flux}_{\text{system 2}} - \text{Net C flux}_{\text{system 1}}) dt \quad (3)$$

Estimating the relative net C flux over time (Eq. 3) requires projections of C emissions and C sequestration rates. In West and Marland (2001), for example, we have examined the typical change in C flows through time when areas under conventional tillage (CT) are converted to no-till (NT) systems. In these analyses, the

tillage practices remain the same, with the same level of agricultural inputs over time. It was assumed that CT had been used historically and that the soil C pool had reached a steady state. Therefore, the rate of soil C accumulation expected for continuation of CT would be zero. In lands changing from CT to NT, we assumed that C would accumulate in the soils and that the initial rate of C accumulation would be maintained for a period of 20 years. The annual rate of C sequestration was assumed to decline linearly for years 21–40, with a new steady state (zero annual sequestration) achieved in year 40. These paths of C sequestration over time were estimated based on data summarized by Johnson et al. (1995); Lal et al. (1998); and Sampson and Scholes (2000), and could be refined for a specific system, a specific crop, or a specific location.

2.2. Carbon sequestration

Once a system has been delineated and the system stocks and flows have been defined, values for the C stocks and flows can be estimated. Estimates of average values for C sequestered in soil due to changes in tillage practice have been calculated (e.g. Kern and Johnson, 1993; Reeves, 1997; Smith et al., 1998). However, in order to update the past reviews and to look at rates of C sequestration as they relate to crop type and other environmental variables, we are currently developing a data base of long-term experiments that have followed changes in soil management. A total of 76 long-term experiments have been compiled and analyzed to date, most from the USA, that monitored changes in SOC under different tillage practices (West and Marland, in preparation). Note that these data reflect a variety of field experiments but do not necessarily reflect a balance of agricultural practices.

In order to illustrate the net effect of changes in agricultural practice on C flows to the atmosphere, we summarize some data on conversion from conventional tillage to no-till. Analyses have been completed for corn, wheat, and soybean in monoculture cropping systems and in rotation with other crop types. An analysis based on all crops in the data base, under both monoculture and rotation cropping, has also been completed. The analysis for all crops includes experiments with cotton, barley, rye, sorghum, oats, alfalfa, sunflower, and clover; in addition to the corn, wheat, and soybeans from the individual analyses. Preliminary results from these analyses are reported here (Fig. 2).

Preliminary analyses suggest that conversion from CT to NT results in net sequestration of C in soil for all crops with the exception of monoculture wheat systems. Carbon accumulation in soil, averaged across all crop types to a depth of 30 cm, was $337 \pm 108 \text{ kg ha}^{-1} \text{ year}^{-1}$ ($n=76$, average experiment duration was 17 years), following a change from CT to NT in monoculture

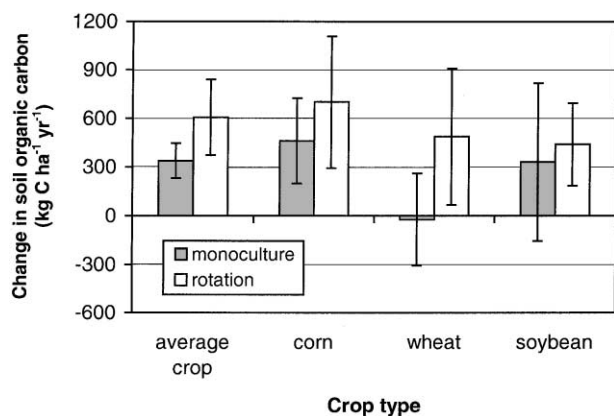


Fig. 2. Average annual soil carbon accumulation to a 30 cm depth for three crops during early years following a change from conventional tillage to no-till. Based on preliminary analysis of data from 76 long-term experiments (see text). Monoculture cropping system represents a single crop grown continuously or in a crop-fallow system; rotation cropping represents a crop grown in rotation with one or more other crop types. Error bars represent 95% confidence interval for the mean observation.

systems. As described previously, the rates of SOC accumulation or loss given here are expected to decline following 20 years of the newly adopted management practice, with SOC reaching a new steady state in approximately 40 years.

Review of 15 experiments on the change of SOC following conversion of wheat monoculture systems from CT to NT did not show a statistically significant change in SOC. While further analysis of the data is necessary to determine the causes of lower SOC or possible loss of SOC, when moving from CT to NT in a monoculture wheat system, one possibility is the decreased soil temperature that commonly accompanies NT practices (Blevins and Frye, 1993). A decrease in soil temperature can result in a shorter growing season and smaller yield, thereby creating less surface residue to be converted to SOC. Of the 15 experiments reviewed, five showed less SOC under NT than under CT, and four of these were conducted in cold temperate regions, north of 45° latitude.

2.3. Carbon emissions

Carbon emissions for agricultural inputs and machinery were calculated using C emission coefficients for primary fuels and electricity, along with data on the fossil fuel requirements of agricultural inputs and machinery (West and Marland, 2001). Carbon dioxide emissions from fossil fuels include the emissions from fossil fuel production, transportation, and combustion. Carbon dioxide emissions from agricultural inputs include those from manufacture, transportation, and application. Carbon dioxide emissions from agriculture machinery include those from production, transportation, and repair of the machinery normalized over the

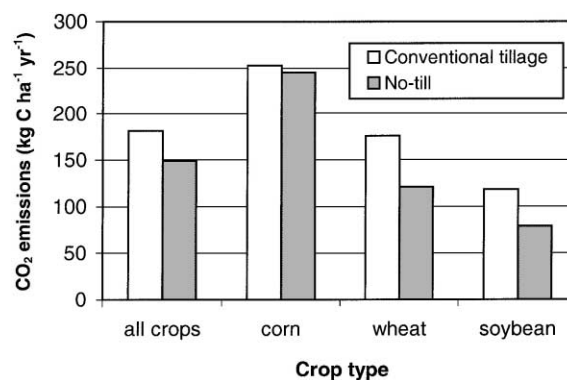


Fig. 3. Carbon dioxide emissions from agricultural inputs (including average use of irrigation water) and machinery for different crop types and tillage practices, using average US agricultural input values for year 1995. Carbon dioxide emissions are from fossil fuels used in the production, transportation, and application of agricultural inputs, and in the production and operation of farm machinery. Based on data in West and Marland (2001).

lifetime of the equipment. Carbon dioxide emissions for agricultural inputs were calculated across crop type and tillage practice using US national average input values (USDA, 1996, 1997a, b). Combining C emissions from both agricultural inputs and machinery (Fig. 3) indicates that practices associated with no-till emit, on average, less C than practices associated with conventional tillage. Unlike the changes in SOC, C emissions associated with management practices are expected to continue indefinitely or until a different management practice is adopted.

3. Results

Combining C emission and C sequestration rates from Figs. 2 and 3, using Eq. (1), allows us to derive values for net C flux (Table 1), which represent the actual impact on atmospheric CO₂ for either continuation with conventional tillage or conversion to no-till. Each management practice; consisting of crop type, tillage, and tillage history; has its respective value for net C flux. For example, the average monoculture corn system with continuation of conventional tillage will discharge C to the atmosphere at a rate of +253 kg C ha⁻¹ year⁻¹, while the same cropping system with conversion to no-till will result in net removal of C from the atmosphere (−215 kg C ha⁻¹ year⁻¹). This is based on US national average emission and sequestration rates. Values for net C flux shown here represent the early years following conversion from CT to NT and do not reflect the expectation that C sequestration in soil will decline with time following the change to no-till (West and Marland, 2001).

Net C flux from conventional tillage systems, as explained previously, represents the baseline values to which any alternative management practices can be

Table 1

Average net carbon flux for three crops with either continuation of conventional tillage or conversion to no-till ($\text{kg C ha}^{-1} \text{ year}^{-1}$)^a

	Corn		Wheat		Soybean		US average crop	
	CT	NT	CT	NT	CT	NT	CT	NT ^b
C sequestration in soil ^c	0	−460	0	+23 ^d	0	−333	0	−337
C emissions from inputs ^e	+181	+222	+109	+98	+50	+56	+113	+125
C emissions from machinery ^f	+72	+23	+67	+23	+67	+23	+69	+23
Net C flux	+253	−215	+176	+144	+117	−254	+182	−189
Relative net C flux		−468		−32		−371		−371

^a Carbon emissions associated with agricultural inputs and machinery are based on energy use and carbon coefficients calculated by West and Marland (2001). Carbon sequestration and flux rates are for early years following conversion of tillage practice.

^b Values for the average US crop using no-till correspond with values in Fig. 1.

^c Values correspond with changes in soil carbon stocks for monoculture cropping systems shown in Fig. 2.

^d See discussion in text.

^e Includes carbon emitted in the production, transport, and application of agricultural inputs (i.e. fertilizer, pesticides, lime, etc.). This analysis includes average use of irrigation water for respective crops in the USA. For crops that do not use irrigation water, the emissions values would be less.

^f Includes carbon emitted from diesel fuel used in farm machinery, and fossil fuel used in the production of farm machinery (i.e. tractor, plow, combine, etc.) normalized over the lifetime of the machines.

compared. A comparison between practices results in a value for relative net C flux. In this comparison between CT and NT, for an average monoculture corn crop, the relative net C flux is $-468 \text{ kg C ha}^{-1} \text{ year}^{-1}$ (Table 1). This value essentially means that the total impact on atmospheric CO_2 , caused by changing from CT to NT, is a reduction of $468 \text{ kg C ha}^{-1} \text{ year}^{-1}$.

In all cases shown in Table 1, the relative net C flux is less than (i.e. more negative than) the value for C sequestration in soil alone, following conversion to no-till. For corn and wheat systems, this indicates that conversion to no-till not only results in C sequestration in the soil but that the reduction in atmospheric CO_2 is augmented by a decrease in C emissions from agricultural operations and inputs. In the case of monoculture wheat systems, while there is a possibility that SOC will decline with a change from CT to NT, the reduction in CO_2 emissions associated with this change is large enough to offset the average loss of SOC and results in a net reduction of atmospheric CO_2 (i.e. relative net C flux of $-32 \text{ kg ha}^{-1} \text{ year}^{-1}$).

Given the trends in C emissions and SOC with time, as previously discussed, the relative net C flux from a monoculture wheat system will be more negative once the loss of SOC ceases after approximately 40 years. Since SOC was increasing under corn and soybean systems, with a change from CT to NT, the relative net C flux increases once SOC reaches a new steady state.

4. Conclusions

When assessing the impact of C sequestration initiatives on the atmospheric CO_2 pool, system boundaries for the affected system must first be established. Carbon

sequestered in the system, as well as that emitted from the system, should be measured or estimated, and all C flows should be evaluated. The net C flux from a single system is considered to be an absolute value. The true effect of a sequestration project, however, is determined not by estimating the absolute net C flux from the new system, but by comparing it with the net C flux that would accompany continuation of the initial system of management. Preliminary results, based on US average data, for conversion from conventional tillage to no-till agriculture, suggest that inclusion of C emissions from agricultural operations and inputs can be important when looking at C sequestration projects. Changes in C emissions from agricultural operations can either enhance or diminish the effect of C sequestration projects on the net C flux to the atmosphere. The analyses reported here represent US average agricultural practices. Changes in SOC accumulation rates will differ on a regional basis due to changes in climate, soil attributes, and cropping practices.

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