

# A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States

Tristram O. West\*, Gregg Marland

*Environmental Sciences Division, Oak Ridge National Laboratory, Bethel Valley Road, P.O. Box 2008, Bldg 1509, M.S. 6335, Oak Ridge, TN 37831-6335, USA*

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## Abstract

The atmospheric CO<sub>2</sub> concentration is increasing, due primarily to fossil-fuel combustion and deforestation. Sequestering atmospheric C in agricultural soils is being advocated as a possibility to partially offset fossil-fuel emissions. Sequestering C in agriculture requires a change in management practices, i.e. efficient use of pesticides, irrigation, and farm machinery. The C emissions associated with a change in practices have not traditionally been incorporated comprehensively into C sequestration analyses. A full C cycle analysis has been completed for agricultural inputs, resulting in estimates of net C flux for three crop types across three tillage intensities. The full C cycle analysis includes estimates of energy use and C emissions for primary fuels, electricity, fertilizers, lime, pesticides, irrigation, seed production, and farm machinery. Total C emissions values were used in conjunction with C sequestration estimates to model net C flux to the atmosphere over time. Based on US average crop inputs, no-till emitted less CO<sub>2</sub> from agricultural operations than did conventional tillage, with 137 and 168 kg C ha<sup>-1</sup> per year, respectively. Changing from conventional tillage to no-till is therefore estimated to both enhance C sequestration and decrease CO<sub>2</sub> emissions. While the enhanced C sequestration will continue for a finite time, the reduction in net CO<sub>2</sub> flux to the atmosphere, caused by the reduced fossil-fuel use, can continue indefinitely, as long as the alternative practice is continued. Estimates of net C flux, which are based on US average inputs, will vary across crop type and different climate regimes. The C coefficients calculated for agricultural inputs can be used to estimate C emissions and net C flux on a site-specific basis. Published by Elsevier Science B.V.

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## 1. Introduction

As the atmospheric concentration of carbon dioxide (CO<sub>2</sub>) grows, there is increasing interest in restraining this growth in order to minimize potential impacts on

the global climate. Although emphasis is focused on decreasing the rate of CO<sub>2</sub> emissions from fossil-fuel use, there is increasing recognition that the rate of emissions can be mitigated by transferring CO<sub>2</sub> from the atmosphere to the terrestrial biosphere.

The United Nations Framework Convention on Climate Change, which entered into force in 1994, recognizes the importance of accounting for net carbon (C) flux when it refers to “emissions by sources

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

fax: +1-865-574-2232.

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

and removals by sinks". The Kyoto Protocol, drafted in 1997 but not yet ratified by enough countries to enter into force, lays forth quantitative, binding commitments for countries to limit emissions of greenhouse gases. In doing so, the Kyoto Protocol affirms that part of the CO<sub>2</sub> emissions from fossil-fuel use, and from other sources, can be offset by removal of CO<sub>2</sub> from the atmosphere via a net increase in the C stocks of the biosphere. Emissions offsets via reforestation and afforestation are endorsed by the Kyoto Protocol now, and sequestration in agricultural soils may be added later. This environmental service by farmers and other landowners could provide a source of carbon-emission credits to be sold to emitters of C and hence provide an additional source of income for farmers.

Conservation tillage, along with efficient management of irrigation, fertilizer, and pesticides, may increase soil organic carbon (SOC) by increasing yields and subsequent organic matter additions to the soil or by decreasing the rate of loss of SOC (Lal et al., 1999). However, C emitted from the manufacture and use of agricultural inputs may negate all or part of the increased C sequestered by soils (Schlesinger, 1999). Debate regarding C sequestration and emissions associated with changes in agricultural practices has continued (Izaurrealde et al., 2000; Schlesinger, 2000), because data on the C inputs to agriculture are uncertain and the inputs are variable across time, place, and crop type.

Indeed, there is a considerable amount of literature on the C benefits of ethanol fuels which raise a similar question—is the apparent savings in emissions from fuel substitution actually counterbalanced by the energy requirements of the system? In the case of ethanol from corn versus gasoline from crude oil, it is clear that there is a net decrease in C emissions to the atmosphere when using ethanol. However, the net decrease is much smaller than suggested if only fuel displacement is considered (Marland and Turhollow, 1991).

This paper examines the energy requirements and subsequent C emissions associated with current agricultural practices in the United States. Data available from the existing literature were used to estimate a full C cycle analysis for agricultural inputs. Calculated emissions values were used with existing data on C sequestration rates to determine the potential changes in net flux of C to the atmosphere when changing from conventional tillage to no-till practices. Spe-

cific objectives were to (1) quantify emissions from standard agricultural practices currently in use; (2) estimate how these emissions might change if existing practices were altered in an effort to sequester C; (3) examine the consequences of a change in management practices on net C flux to the atmosphere; and (4) extend the estimated impact on net C flux over time. The analysis was expected to indicate whether less intense tillage practices (i.e. reduced tillage or no-till) result in less net C flux to the atmosphere. The analysis was further expected to indicate how net C flux might change with time, as SOC approaches a new steady state associated with new tillage practices, and while the new suite of management practices is continued. The data reflect average practice in the US in the mid 1990s.

## 2. Carbon emissions from fuel consumption and agricultural inputs

### 2.1. Fuels and electricity

Use of fossil fuels in agriculture results in CO<sub>2</sub> emissions from the combustion of fuels, and there are additional emissions associated with production and delivery of fuels to the farm. Carbon emissions attributed to fossil fuels were estimated using existing C coefficients (EIA, 1999), higher heating values (EIA, 1999b), fuel chemistry, and the energy consumed during production and transport of the fuels (Table 1).

The energy required for production and transport of one unit of coal, natural gas, and refined petroleum products was taken to be 3, 6, and 16% of the energy content of the fuel combusted, respectively (US Office of Technology Assessment (OTA), 1990). The input/output methodology for estimating the energy inputs for primary fuels was documented by Casler and Hannon (1989). While the OTA analysis shows the total primary energy input for delivery of a unit of energy output, the assumption used here is that the input to each fuel is of its own type, i.e. that the 3% primary energy supplement for production and transport of coal is supplied by coal and the 16% primary energy supplement for production, refining, and transport of refined petroleum products is supplied by petroleum products. This may have a slight distortion on CO<sub>2</sub> emissions by assuming, for example, that the energy for transporting coal is supplied by

Table 1  
Carbon dioxide emissions from production and combustion of fossil fuels

Fuel	At point of fuel combustion <sup>a</sup> (kg C GJ <sup>-1</sup> )	Due to production and transport of fuel <sup>b</sup> (kg C GJ <sup>-1</sup> )	Total from fuel use (kg C GJ <sup>-1</sup> )
Primary fuel			
Motor gasoline	18.34	2.93	21.27
Distillate fuel (diesel)	18.92	3.03	21.95
Residual fuel	20.19	3.23	23.42
Liquified petroleum gas	16.11	2.58	18.69
Petroleum coke	26.41	4.23	30.64
Naphtha	18.84	3.01	21.85
Coal <sup>c</sup>	24.43	0.73	25.16
Natural gas	13.72	0.82	14.54
Waste fuel			
Tires	22.19	0.07	22.27
Wood	25.32	0.12	25.44

<sup>a</sup> Carbon equivalent values for primary fuels, tires, and wood chips from EIA (1999), WRI (1986), and Wright et al. (1992), respectively. Based on higher heating value (HHV) of fuel.

<sup>b</sup> Based on input/output tables from US Office of Technology Assessment (1990) for primary fuels. No production costs are associated with waste fuels. If wood is produced intentionally for fuel use, then the production and transport value would be estimated at 1.34 kg C GJ<sup>-1</sup>, which includes energy for production and harvesting of biomass (Wright et al., 1992). Transportation of wood and tires is based on 1.4 MJ Mg<sup>-1</sup> km<sup>-1</sup> (Börjesson, 1996); HHV of 19.77 and 37.80 GJ Mg<sup>-1</sup> for hardwoods (Wright et al., 1992) and tire-derived fuel (Waste Recovery Inc., 1986), respectively; and an assumed hauling distance of 80 km. Energy used in fractionation of tires is not included.

<sup>c</sup> Based on the average coal used by US electric utilities in 1998.

more carbon-intensive coal rather than by petroleum products.

Non-traditional fuels sometimes used in processing agricultural materials include scrap tires and biomass, and these were included here for completeness (Table 1). The rate of C emission from the incineration of tires was calculated from the average C content of tires (83.87%) and a higher heating value of 37,798 kJ kg<sup>-1</sup> (Waste Recovery Inc., 1986). Transportation of biomass and tires was based on a transportation energy rate of 1.4 MJ Mg<sup>-1</sup> km<sup>-1</sup> (Börjesson, 1996), which is similar to the value of 1.8 MJ Mg<sup>-1</sup> km<sup>-1</sup> used by Fluck (1992), and an average haul distance of 80 km (Boman and Turnbull, 1997; Turhollow and Perlack, 1991).

Carbon dioxide emissions attributable to electricity consumption are based on the fuels used in power generation and reflect the US mean generation mix in 1998 (Table 2). The fuel mix is for all electrical generation in the US, while data on net plant efficiency, required to estimate fuel use per kWh(e) and, hence, CO<sub>2</sub> emissions per kWh(e), were available only for utility owned plants, which constituted 89% of total US electricity generation.

Nuclear and renewable fuels do not result in net emissions of CO<sub>2</sub> at the power plant (with the exception of some geothermal plants) but do have associated emissions from fuel enrichment (nuclear), fuel collection and transport (biomass), etc. These contributions tend to be small for nuclear, hydrologic, and renewable fuels (Mortimer, 1991; Rashad and Hammad, 2000; Turhollow and Perlack, 1991), and were taken to be zero in this analysis. At the next level of detail, there are also CO<sub>2</sub> emissions during the construction of a power plant (i.e. from fuel use, cement manufacture, site preparation, etc.), but these tend to be small when averaged over the lifetime of a power plant (Boustead and Hancock, 1979; Rashad and Hammad, 2000) and were similarly ignored in this analysis.

Biomass fuels do, of course, result in emissions of CO<sub>2</sub> at the point of combustion that are similar to those for fossil fuels. In theory, a sustainable biomass crop or biomass waste product will have CO<sub>2</sub> emissions at the point of combustion balanced by photosynthetic uptake of CO<sub>2</sub> at the point of biomass growth. The perspective adopted by the Intergovernmental Panel on Climate Change (Houghton et al., 1997), and embraced here, is that any net emissions associated with

Table 2  
Carbon dioxide emissions from generation of electricity in the United States

Primary fuel	At point of fuel combustion <sup>a</sup> (kg C kWh(e) <sup>-1</sup> )	Due to production and transport of fuel <sup>b</sup> (kg C kWh(e) <sup>-1</sup> )	Total from fuel use (kg C kWh(e) <sup>-1</sup> )	Contribution to US power generation <sup>a</sup> (%)
Coal	0.274	0.008	0.282	51.85
Petroleum	0.225	0.036	0.261	3.51
Gas	0.156	0.009	0.165	15.19
Other <sup>c</sup>	0.000	0.000 <sup>d</sup>	0.000	29.45
Total US average	0.173	0.007	0.180	100.00

<sup>a</sup> Based on fuel used and net energy generated from US electric utilities in 1998 (EIA, 2000).

<sup>b</sup> Based on US Office of Technology Assessment (1990). Emissions are related to operating costs and do not include emissions related to capital, e.g. the emissions from power plant construction.

<sup>c</sup> Includes 18.64% nuclear, 8.82% hydro, and 1.98% as the sum of geothermal, wind, solar, wood, and waste.

<sup>d</sup> Carbon dioxide emissions related to production and transport of nuclear and renewable fuels are shown here to be zero, although there are small quantities of CO<sub>2</sub> emissions related to nuclear fuel preparation; geothermal flows; and harvest, transport, and any non-sustainable production of biomass fuels.

non-replacement harvest of biomass will be captured in a decreasing mass of C stored in the terrestrial biosphere and efforts to account for this in the energy sector are at risk of double counting net emissions to the atmosphere.

## 2.2. Fertilizers and agricultural lime

The fertilizer industry deals primarily with supplying nitrogen (N), phosphorus (P), and potassium (K), although chemical fertilizers are used to supply 13 essential plant nutrients (Mudahar and Hignett, 1987). This analysis includes the three primary nutrients, plus agricultural lime (CaCO<sub>3</sub>) in the form of crushed limestone (Table 3). Carbon dioxide emissions result from the energy required for production of fertilizers plus the energy required for their transport and application. The energy required per tonne of N and phosphate (P<sub>2</sub>O<sub>5</sub>) varies considerably with the form in which the nutrient is supplied. The weighted mean values for N and P<sub>2</sub>O<sub>5</sub> applied in the US are used here. This data originates from the latest survey data taken in 1987 by The Fertilizer Institute (1988). Most of the data on the energy requirements for fertilizer production are based on US facilities.

Carbon emissions from fossil fuels used in the production of fertilizers include emissions from mineral extraction and fertilizer manufacture (Bhat et al., 1994). Post-production emissions can include those from packaging, transportation, and field application of fertilizer (Mudahar and Hignett, 1987). In

the US, fertilizers used on farms are commonly sold and transported in bulk form (Mudahar and Hignett, 1982), therefore energy used in packaging was not included in these calculations. Emissions due to fertilizer application were dealt with separately and in later calculations of energy use associated with the operation of farm machinery.

Carbon emissions from agricultural lime were calculated from the fuel used for mining limestone (US Department of Commerce, 1992) and for grinding the stone into a usable product (Mudahar and Hignett, 1987). Energy and C emissions associated with agricultural lime are reported here in CaCO<sub>3</sub> equivalent units. In the calculations here, calcitic limestone was assumed to be 95% CaCO<sub>3</sub> (Brady and Weil, 1996). Agricultural lime, like fertilizers, was assumed to be sold and transported in bulk form. Energy used in the transportation of fertilizers and lime was based on a fuel-use rate of 0.7 and 1.4 MJ Mg<sup>-1</sup> km<sup>-1</sup> for railroad and truck transport, respectively (Börjesson, 1996). Average transportation distance was assumed to be 800 and 160 km by railroad and truck, respectively (Mudahar and Hignett, 1982).

Data on the energy balance of fertilizer production (Bhat et al., 1994; Mudahar and Hignett, 1987) report steam requirements without documenting the fuel used to raise steam. The assumption here is that all steam required for production of N fertilizers is raised by burning natural gas. In the production of ammonia and urea, some plants produce excess steam that is not used in the production process. Typically

Table 3  
Fossil fuel energy requirements and carbon dioxide emissions from production of fertilizer and agricultural lime

	N		P <sub>2</sub> O <sub>5</sub>		K <sub>2</sub> O		CaCO <sub>3</sub>	
	In GJ Mg <sup>-1</sup>	In kg C Mg <sup>-1</sup>	In GJ Mg <sup>-1</sup>	In kg C Mg <sup>-1</sup>	In GJ Mg <sup>-1</sup>	In kg C Mg <sup>-1</sup>	In GJ Mg <sup>-1</sup>	In kg C Mg <sup>-1</sup>
Production <sup>a</sup>								
Natural gas	51.81	753.32	0.63	9.16	2.69	39.11	0.006	0.09
Electricity <sup>b</sup>	2.76	47.31	5.37	92.06	2.11	36.17	0.375	6.43
Distillate fuel	0.01	0.22	0.40	8.78	0.00	0.00	0.033	0.72
Steam <sup>c</sup>	0.91	13.23	-1.87	0.00	-	-	-	-
Coal	-	-	-	-	-	-	0.003	0.08
Gasoline	-	-	-	-	-	-	0.004	0.09
Production total	55.48	814.08	4.52	110.00	4.80	75.28	0.421	7.41
Post-production <sup>d</sup>								
Distillate fuel	1.98	43.46	2.51	55.09	2.05	45.00	1.29	28.32
Fertilizer total <sup>e</sup>	57.46	857.54	7.03	165.09	6.85	120.28	1.71	35.73

<sup>a</sup> Production of N, P, and K include the extraction of nutrients and manufacture of fertilizer in 1987 (Bhat et al., 1994). Production of agricultural lime includes energy used in mining (United States Department of Commerce, 1992) and grinding (Mudahar and Hignett, 1987) limestone.

<sup>b</sup> Energy input from electricity is given as the primary energy input required for power generation and is based on 10.5 MJ kWh(e)<sup>-1</sup> (0.0105 GJ kWh(e)<sup>-1</sup>).

<sup>c</sup> Demands for steam are assumed to be met by combustion of natural gas unless otherwise specified in the primary literature. In the production of phosphate fertilizers, some facilities produce a net excess of steam that is typically exported to other industries. This analysis does not include a CO<sub>2</sub> emissions credit for this excess steam (see text).

<sup>d</sup> Post-production consists of transportation of the mineral to the production facility, supply center, and the site of application. Energy used in transportation is 0.7 and 1.4 MJ Mg<sup>-1</sup> km<sup>-1</sup> by railroad and truck, respectively (Börjesson, 1996). Distance of transportation is assumed to be 800 and 160 km by railroad and truck, respectively (Mudahar and Hignett, 1982). Energy used in fertilizer application is included in later calculations (see Table 7).

<sup>e</sup> Total values may not equal sums due to independent rounding.

this steam is exported to other manufacturing industries, and Bhat et al. (1994) treated it as a credit in the energy balance of fertilizer production. This energy balance credit comprised less than 2% of the total energy input into the production of N fertilizers and was not included in the estimate of CO<sub>2</sub> emissions.

Similarly, production of P fertilizers typically results in generation and export of excess steam. Sulfuric acid plants, that are generally run in conjunction with phosphoric acid production, generate and export excess steam that can equal 40% of the gross energy requirement for P<sub>2</sub>O<sub>5</sub> production. Because much of this steam export appears to be generated from the burning of sulfur, and hence without CO<sub>2</sub> emissions, it is included in the energy balance summarized here but ignored in the CO<sub>2</sub> balance. Recently, revised calculations by Anthony Turhollow (personal communication, 2000) indicate that natural gas used in the production of P<sub>2</sub>O<sub>5</sub> may be more than previously

indicated and could increase the associated C emissions by approximately 20%.

### 2.3. Pesticides

Modern pesticides are almost entirely produced from crude petroleum or natural gas products. The total energy input is thus both the material used as feedstock and the direct energy inputs. Carbon dioxide emissions from production of pesticides (Table 4) consist of both of these contributions to manufacture the active ingredient. Post-production emissions include those from formulation of the active ingredients into emulsifiable oils, wettable powders, or granules; and those from packaging, transportation, and application of the pesticide formulation.

Carbon dioxide emissions from pesticide use were estimated for specific pesticide classes by calculating average values of energy input for the production and application of individual pesticides (Green, 1987).

Table 4

Fossil fuel energy requirements and carbon dioxide emissions from production of pesticides

	Herbicide		Insecticide		Fungicide	
	In GJ Mg <sup>-1</sup>	In kg C Mg <sup>-1</sup>	In GJ Mg <sup>-1</sup>	In kg C Mg <sup>-1</sup>	In GJ Mg <sup>-1</sup>	In kg C Mg <sup>-1</sup>
Production <sup>a</sup>						
Naphtha	71.99	1572.98	63.31	1383.32	92.20	2014.57
Natural gas	43.04	625.80	49.78	723.80	31.10	452.19
Coke	0.32	9.80	0.77	23.59	0.00	0.00
Distillate fuel	12.31	270.20	7.86	172.53	11.10	243.65
Electricity <sup>b</sup>	71.68	1228.80	92.13	1579.37	78.15	1339.71
Steam <sup>c</sup>	44.22	642.96	47.97	697.48	53.34	775.56
Production total	243.56	4350.54	261.82	4580.09	265.88	4825.68
Post-production <sup>d</sup>						
Distillate fuel	2.00	43.90	2.00	43.90	2.00	43.90
Electricity <sup>b</sup>	1.00	17.14	1.00	17.14	1.00	17.14
Natural gas	20.00	290.80	20.00	290.80	20.00	290.80
Post-production total	23.00	351.84	23.00	351.84	23.00	351.84
Pesticide total	266.56	4702.38	284.82	4931.93	288.88	5177.52

<sup>a</sup> Based on weighted amount of pesticides used on corn, wheat, and soybean crops in the United States in 1996, using pesticide energy values from Green (1987).

<sup>b</sup> Energy input from electricity is given as the primary energy input required for power generation and is based on 10.5 MJ kWh(e)<sup>-1</sup> (0.0105 GJ kWh(e)<sup>-1</sup>).

<sup>c</sup> Demands for steam are assumed to be met by combustion of natural gas.

<sup>d</sup> Includes formulation, packaging, and transportation (Green, 1987). The energy for formulation is assumed to be from natural gas, the energy for packaging an equal mix from electricity and distillate fuel, and the energy for transportation from diesel fuel. Energy used in post-production processing is assumed to be the same for the different pesticides and for their respective formulations. Energy used in pesticide application is included in later calculations (see Table 7).

Carbon dioxide emissions for currently used pesticides were estimated by assigning 64 herbicides, insecticides, and fungicides used on US corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L.) crops in 1996 (Fernandez-Cornejo and Jans, 1999) to their respective pesticide classes and calculating weighted averages of the C emissions based on the relative amounts of pesticides used. It was again assumed, unless specified otherwise, that steam was raised by burning natural gas. Energy balances for production of some pesticides are rough approximations only, but Green (1987) suggested that values may be within  $\pm 10\%$  for some of the best known and most widely used pesticides.

#### 2.4. Irrigation

Irrigation water in the US is obtained primarily from on-farm wells, on-farm surface reservoirs, and off-farm surface reservoirs (Table 5). Fossil fuels used to power pumps, which distribute irrigation water, were calculated using energy expenses for on-farm

pumping (US Department of Commerce, 1997) and energy price estimates (EIA, 2000b). The energy use and C emissions from pumping water were applied to both on-farm wells and off-farm surface reservoirs. It was assumed that the average energy and CO<sub>2</sub> cost of pumping water is the same per ha-m of water for the two sources (USDA, 1997a). The energy cost of collecting and distributing on-farm surface water, powered primarily by gravitational forces, was considered to be negligible.

#### 2.5. Seed production

Different methods for calculating energy use in seed production have been reviewed and compared (Heichel, 1980). Heichel (1980) concluded that the most accurate method would be to calculate a detailed energy budget for each crop, including energy for seed cleaning and packaging of the seed. Heichel further concluded that, lacking these detailed energy budgets, the next best method was to estimate energy costs using the retail cost of seeds in conjunction

Table 5  
Annual fossil fuel energy requirements and carbon dioxide emissions from collection, storage, and use of irrigation water

Fuel use and irrigation type	Area irrigated by fuel type <sup>a</sup> (million ha)	Energy required <sup>b</sup> (GJ ha <sup>-1</sup> )	CO <sub>2</sub> emissions		Area irrigated by irrigation type <sup>a</sup> (%)
			In kg C ha <sup>-1</sup>	In kg C ha-m <sup>-1c</sup>	
On-farm pump					
Electricity	8.00	5.32	266.00	–	–
Natural gas	2.46	19.61	285.13	–	–
LPG	0.65	6.70	125.22	–	–
Distillate fuel	3.33	7.53	165.28	–	–
Gasoline	0.07	5.92	125.92	–	–
Total on-farm pump	14.48	8.31	239.17	597.93	–
Total on-farm wells <sup>d</sup>	–	8.31	239.17	597.93	62.08
Total on-farm surface	–	0.00	0.00	0.00	12.77
Total off-farm surface	–	15.17	436.49	597.93	29.99
Total US average <sup>e</sup>	–	9.26	266.48	525.10	104.84

<sup>a</sup> Data from US Department of Commerce (1997). Totals for columns may not equal sums of individual values due to independent rounding.

<sup>b</sup> Based on 1994 irrigation data (US Department of Commerce, 1997) and 1994 energy prices (EIA, 2000b).

<sup>c</sup> Average depth of water applied in 1994 was 0.40, 0.43, and 0.73 m for on-farm pump, on-farm surface, and off-farm surface, respectively (US Department of Commerce, 1997). Data were not available for the amount of water applied with respect to the primary fuel used.

<sup>d</sup> Irrigation water from on-farm wells is primarily derived from a pump system; energy used for off-farm surface water collection is assumed to be the same per ha-m of water as that for on-farm pump water, and energy used for on-farm surface water collection and distribution is assumed to be negligible (USDA, 1997a).

<sup>e</sup> The total area is greater than 100% because some areas are irrigated using more than one irrigation practice and are counted twice in the US agriculture survey data. The total weighted energy and carbon emission values shown here have been normalized to 100% coverage.

Table 6  
Fossil fuel energy requirements and carbon dioxide emissions from seed production

Seed	Cost <sup>a</sup> (US\$ kg <sup>-1</sup> )	Energy <sup>b</sup> (MJ kg <sup>-1</sup> )	C emissions <sup>c</sup> (kg C per kg seed)
Grain seed			
Barley ( <i>Hordeum vulgare</i> L.)	0.26	5.57	0.11
Corn ( <i>Zea Mays</i> L.)	2.49	53.36	1.05
Cotton ( <i>Gossypium hirsutum</i> L.)	1.54	33.00	0.65
Oats ( <i>Avena sativa</i> L.)	0.29	6.21	0.12
Sorghum ( <i>Sorghum bicolor</i> L.)	2.03	43.50	0.86
Soybean ( <i>Glycine max</i> L.)	0.60	12.86	0.25
Wheat, spring ( <i>Triticum aestivum</i> L.)	0.31	6.64	0.13
Wheat, winter ( <i>Triticum aestivum</i> L.)	0.26	5.57	0.11
Forage seed			
Alfalfa ( <i>Medicago sativa</i> L.)	6.21	133.08	2.63
Orchardgrass ( <i>Dactylis glomerata</i> L.)	2.62	56.15	1.11
Red clover ( <i>Trifolium pratense</i> L.)	4.06	87.01	1.72
Ryegrass ( <i>Lolium perenne</i> L.)	1.28	27.43	0.54
Timothy ( <i>Phleum pratense</i> L.)	1.61	34.50	0.68

<sup>a</sup> Seed prices from USDA (1997c).

<sup>b</sup> Using dollar to energy conversion of 21.43 MJ US\$<sup>-1</sup> for agricultural products (US Office of Technology Assessment, 1990).

<sup>c</sup> Fuel mix contributing to C emissions is assumed to consist of fuel oil (50%), natural gas (20%), and electricity (30%) (Börjesson, 1996).

with the current average dollar-to-energy transformation coefficient for agriculture. Energy used in seed production, packaging, and distribution (Table 6) was estimated from current seed prices (USDA, 1997c) and a dollar-to-energy conversion factor for general agricultural products (US Office of Technology Assessment, 1990). Carbon emissions were calculated with the assumption that energy used in seed production consisted of a 50, 20, and 30% mix of fuel oil, natural gas, and electricity, respectively (Börjesson, 1996).

### 3. Carbon emissions relative to tillage practice and crop type

Emissions of CO<sub>2</sub> from agriculture are generated from three sources: machinery used for cultivating the land, production and application of fertilizers and pesticides, and the SOC that is oxidized following soil disturbance. The amount of soil that is disturbed, in turn causing decomposition and oxidation of SOC, is largely dependent on the tillage practices used. The amount of fertilizers and pesticides applied varies among crop types, crop rotations, and tillage practices.

The term conventional tillage (CT) represents tillage practices that leave less than 15% residue

cover after planting. Reduced tillage (RT) represents practices that leave 15–30% residue cover. Conservation tillage is any practice that leaves greater than 30% residue after planting; this latter category includes no-till (NT) (Conservation Technology Information Center, 1998). Conventional tillage usually involves the use of plowing, while reduced tillage involves using disks or chisels, without the use of plows. No-till leaves the soil undisturbed. In this analysis, CT is any practice that uses a moldboard plow, RT includes practices that do not use a moldboard plow, and NT leaves the soil relatively undisturbed.

#### 3.1. Farm machinery

Energy and CO<sub>2</sub> emissions associated with different tillage practices (Table 7) are a consequence of the fuel used by farm machines and the energy consumed in manufacture, transportation, and repair of the machines (Bowers, 1992). While CO<sub>2</sub> emissions associated with the application of fertilizers and pesticides were calculated along with other farm operations (Table 7), they do not occur on all fields and in all years, as do other farm operations. Therefore, CO<sub>2</sub> emissions from the application of

Table 7

Annual fossil fuel energy requirements and carbon dioxide emissions from agriculture machinery for different tillage practices in the United States, circa 1990

Farm operation	Diesel fuel used in machine operation		Energy in MTR <sup>a</sup> (MJ ha <sup>-1</sup> )	Carbon emissions (kg C ha <sup>-1</sup> )	CT <sup>b</sup> (kg C ha <sup>-1</sup> )	RT <sup>b</sup> (kg C ha <sup>-1</sup> )	NT <sup>b</sup> (kg C ha <sup>-1</sup> )
	In l ha <sup>-1</sup>	In MJ ha <sup>-1</sup>					
Moldboard plow	21.78 <sup>c</sup>	1122	102	26.75	26.75	–	–
Disk	6.70 <sup>d</sup>	345	55	8.72	17.44 <sup>h</sup>	17.44 <sup>h</sup>	–
Planting	4.93 <sup>e</sup>	254	58	6.79	6.79	6.79	6.79
Single cultivation <sup>i</sup>	3.26 <sup>f</sup>	168	42	4.57	4.57	4.57	–
Fertilizer application	9.82 <sup>g</sup>	506	60	12.35	–	–	–
Pesticide application	1.22 <sup>g</sup>	63	56	2.54	–	–	–
Harvest w/combine	11.14 <sup>g</sup>	574	186	16.47	16.47	16.47	16.47
Total C emissions							
Corn					72.02	45.27	23.26
Soybean and wheat <sup>i</sup>					67.45	40.70	23.26

<sup>a</sup> Energy embodied in manufacturing, transportation, and repair of machinery is from residual fuel (25%), distillate fuel (10%), coal (45%), electricity (8%), and human labor (12%) (Bowers, 1992; Boustead and Hancock, 1979; and Graedel and Allenby, 1995). Energy from human labor is not included in calculations for carbon emissions, because it is assumed that humans will respire carbon dioxide regardless of whether they are working.

<sup>b</sup> CT, RT, and NT are conventional till, reduced till, and no-till, respectively.

<sup>c</sup> Sources of data for calculations of average fuel use are Collins et al. (1980), Gumbs and Summers (1985), Plouffe et al. (1995), Shelton (1980), Sijtsma et al. (1998), Tompkins and Carpenter (1980).

<sup>d</sup> Sources of data for calculations of average fuel use are Collins et al. (1980), Shelton (1980), Sijtsma et al. (1998), Smith (1993), Tompkins and Carpenter (1980).

<sup>e</sup> Sources of data for calculations of average fuel use are Collins et al. (1980), Tompkins and Carpenter (1980).

<sup>f</sup> Sources of data for calculations of average fuel use are Shelton (1980), Smith (1993).

<sup>g</sup> Source of data for calculation of average fuel use is Bowers (1992).

<sup>h</sup> Disking was counted twice to represent two passes over the field.

<sup>i</sup> Single cultivation is not included in analyses for wheat, soybean, or other non-row crops.

<sup>j</sup> Since fertilizer and pesticide application does not necessarily occur on an annual basis, the associated C emissions need to be weighted with respect to the percentage of crops using fertilizers and pesticides (see Table 8).

fertilizers and pesticides are weighted by their extent of application and are included in Table 8.

### 3.2. Crop inputs

Carbon dioxide emissions from specific crop inputs are given for corn, soybean, and wheat (Table 8). Agronomic inputs were calculated from the US national average use of fertilizers, pesticides, irrigation, and other production inputs. National average data were available as a function of crop type and tillage intensity for all inputs except lime and irrigation, and for these, data were available for crop type only. This analysis assumes that the need for lime does not change with the intensity of tillage.

United States data for 1995 show that herbicide use was greater, and insecticide use less, going from CT

to RT to NT (USDA, 1997b) (Table 8). Although the decreased use of insecticides with no-till appears to be contrary to traditional agronomic findings, a recent study that reviewed past estimates of national insecticide use confirmed this trend and concluded that insecticide use with NT is no more than that with CT, and is often less (Day et al., 1999). Fungicides were not included in the accounting, because the contribution is negligible and data were not available. Carbon emissions from the application of fertilizers, pesticides, and lime were combined with their respective C emissions from production on a per crop basis, and the emissions total weighted by the percentage of planted area using the respective treatments. Emissions from application were included with emissions from production separately for herbicides and insecticides since they are typically applied separately. Emissions from

Table 8

Annual average US agricultural inputs and associated carbon dioxide emissions for corn, soybean and winter wheat crops using three different tillage practices in 1995

Agricultural input	Conventional till			Reduced till			No-till		
	In kg ha <sup>-1a,b</sup>	In kg C ha <sup>-1</sup>	% <sup>c</sup>	In kg ha <sup>-1a,b</sup>	In kg C ha <sup>-1</sup>	% <sup>c</sup>	In kg ha <sup>-1a,b</sup>	In kg C ha <sup>-1</sup>	% <sup>c</sup>
<b>(a) Corn crops</b>									
Herbicide <sup>d</sup>	2.71	15.28	93	2.96	16.46	96	3.63	19.61	99
Insecticide <sup>d</sup>	0.99	7.42	24	0.85	6.73	27	0.68	5.89	22
Fungicide <sup>e</sup>	–	–	–	–	–	–	–	–	–
N <sup>f</sup>	107.60	104.62	93	148.00	139.27	98	150.20	141.15	98
P <sub>2</sub> O <sub>5</sub>	56.00	9.25	83	66.10	10.91	81	62.80	10.37	79
K <sub>2</sub> O	74.00	8.90	71	94.20	11.33	81	85.18	10.25	65
CaCO <sub>3</sub> <sup>f</sup>	3800.00	135.77	5	3800.00	135.77	5	3800.00	135.77	5
Seed	20.47	21.49	100	20.47	21.49	100	20.47	21.49	100
Irrigation water <sup>b</sup>	0.32	168.04	15	0.29	152.28	15	0.25	131.28	15
Total C emissions		180.77			223.24			221.86	
Total (0% irrigation)		155.56			200.40			202.17	
Total (100% irrigation)		323.60			352.68			336.45	
<b>(b) Soybean crops</b>									
Herbicide <sup>d</sup>	1.12	7.81	98	1.21	8.23	96	1.50	9.59	99
Insecticide <sup>d</sup>	0.64 <sup>g</sup>	5.70	2	0.55	5.25	2	0.39	4.46	2
Fungicide <sup>e</sup>	–	–	–	–	–	–	–	–	–
N <sup>f</sup>	12.30	22.90	16	34.70	42.11	16	29.10	37.30	18
P <sub>2</sub> O <sub>5</sub>	59.40	9.81	14	67.30	11.11	21	57.20	9.44	23
K <sub>2</sub> O	89.70	10.79	14	96.40	11.59	26	107.70	12.95	29
CaCO <sub>3</sub> <sup>f</sup>	4000.00	142.92	4	4000.00	142.92	4	4000.00	142.92	4
Seed	81.17	20.29	100	81.17	20.29	100	81.17	20.29	100
Irrigation water <sup>b</sup>	0.38	199.54	5	0.34	178.54	5	0.30	157.53	5
Total C emissions		50.30			55.02			56.11	
Total (0% irrigation)		40.32			46.10			48.23	
Total (100% irrigation)		239.86			224.64			205.76	
<b>(c) Winter wheat crops</b>									
Herbicide <sup>d</sup>	0.22	3.57	68	0.31	4.00	56	0.40	4.42	44
Insecticide <sup>d</sup>	0.48 <sup>g</sup>	4.91	6	0.41	4.56	6	0.33 <sup>g</sup>	4.17	6
Fungicide <sup>e</sup>	–	–	–	–	–	–	–	–	–
N <sup>f</sup>	70.60	72.89	93	37.00	44.08	87	58.30	62.34	93
P <sub>2</sub> O <sub>5</sub>	77.30	12.76	70	40.40	6.67	53	50.40	8.32	76
K <sub>2</sub> O	88.50	10.64	10	62.80	7.55	15	77.30	9.30	52
CaCO <sub>3</sub> <sup>f</sup>	3800.00	135.77	1	3800.00	135.77	1	3800.00	135.77	1
Seed	175.27	19.28	100	175.27	19.28	100	175.27	19.28	100
Irrigation water <sup>b</sup>	0.20	105.02	7	0.18	94.52	7	0.16	84.02	7
Total C emissions		108.50			72.78			97.85	
Total (0% irrigation)		101.14			66.17			91.97	
Total (100% irrigation)		206.16			160.69			175.99	

<sup>a</sup> All agricultural inputs based on 1995 data. National average inputs for pesticides from USDA (1997b); for fertilizers, lime, and irrigation (USDA, 1997a); and for seed production (USDA, 1996). Data give the mean application rate for all hectares that were treated.

<sup>b</sup> Units for irrigation water are ha-m ha<sup>-1</sup>.

<sup>c</sup> Percent of planted hectares treated in 1995.

<sup>d</sup> Carbon dioxide emissions for herbicides and insecticides include C emissions from pesticide application (2.54 kg C ha<sup>-1</sup>) calculated in Table 7.

<sup>e</sup> Fungicides are applied on less than 1% of crop lands and data on quantities applied are not available.

<sup>f</sup> Carbon dioxide emissions for N fertilizers include C emissions from fertilizer application (12.35 kg C ha<sup>-1</sup>) calculated in Table 7. It is assumed that if P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O are applied, they would be applied in conjunction with N application, therefore additional emissions for application are not included with P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O. Lime is expected to be applied separately from fertilizers, therefore emissions from application (12.35 kg C ha<sup>-1</sup>) are added to the emissions from lime production.

<sup>g</sup> Data were not available; values shown were estimated using data from other crops.

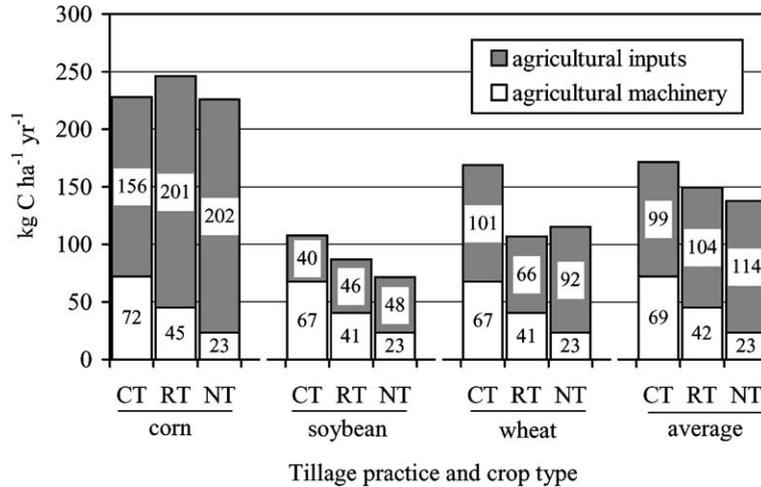


Fig. 1. Total US average carbon dioxide emissions for three crop types using three different tillage practices. CT, RT, and NT are conventional tillage, reduced tillage, and no-till, respectively. The graph is for non-irrigated areas, which comprise 85% (by area) of US corn crops, 95% of soybean crops, and 93% of wheat crops. Carbon dioxide emissions from agricultural inputs (fertilizers, pesticides, seeds, etc.) and machinery are from Tables 7 and 8, respectively.

fertilizer application are included only for N fertilizer, because it was assumed that if P and K were being applied, they would have been included with the application of N.

The volume of irrigation water applied for each crop type (USDA, 1997a) was adjusted with respect to tillage practice based on calculations by Harman et al. (1998). Harman et al. (1998) found that irrigation for corn generally declined 25% when using NT as opposed to CT, while irrigation for sorghum using NT decreased approximately 50%. In this study, a 25% reduction in irrigation volume was used for NT and a 12% reduction was used for RT—on all crop types. Since crops, depending on the region in which they are located, either use or do not use irrigation water, this analysis shows C emissions for an average irrigation volume over all planted areas, but also shows emissions for areas that are irrigated or are not irrigated.

Seeding rates used for corn, soybean, and wheat in 1995 were 20.47, 81.17, and 175.27 kg ha<sup>-1</sup>, respectively (USDA, 1996). Seeding rates were assumed to be similar across the different tillage intensities, but it is noted that NT crops may require up to 20% more seeds to produce the same yield as crops using CT (Frye, 1984).

### 3.3. Combined emissions from machinery and inputs

Emissions of CO<sub>2</sub> from farm machinery (Table 7) were combined with emissions from agricultural inputs on non-irrigated lands (Table 8) to estimate total CO<sub>2</sub> emissions as a function of crop and tillage practice (Fig. 1). Calculations of total CO<sub>2</sub> emissions show that corn crops generate the largest amount of emissions per unit area cultivated, with soybeans generating the least. The difference between the two crops is largely attributed to N fertilizer use. On average, NT practices generate less CO<sub>2</sub> emissions from agricultural inputs and machinery combined than do CT practices, with the exception of corn crops, where emissions from CT and NT are approximately equal (Fig. 1).

## 4. Net effect on atmospheric CO<sub>2</sub> from changing tillage practices

Net C flux is defined here as the difference between C sequestered in the soil and the total C emissions from all farm inputs and operations (Table 9). Net C flux provides an estimate of the actual impact on the

Table 9  
Average net carbon flux for US agriculture with changes in tillage practices

	Conventional till <sup>a</sup> (kg C ha <sup>-1</sup> per year)	No-till <sup>a</sup> (kg C ha <sup>-1</sup> per year)
C sequestration in soil <sup>b</sup>	0	-337
C emissions from machinery <sup>c</sup>	+69	+23
C emissions from agricultural inputs <sup>d</sup>	+99	+114
Net C flux	+168	-200
Relative net C flux <sup>e</sup>	0	-368

<sup>a</sup> Negative and positive values indicate reductions and additions to atmospheric C pool, respectively.

<sup>b</sup> C sequestration values are preliminary results from the US Department of Energy, Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystem's (CSiTE) data base of 76 long-term soil carbon experiments. Carbon sequestration rates are per 30 cm depth.

<sup>c</sup> Averaged from total C emissions for corn, soybean, and wheat crops (Table 7).

<sup>d</sup> Averaged from total C emissions (not including irrigation water) for corn, soybean, and wheat crops (Table 8).

<sup>e</sup> Relative net C flux represents the difference between the net C fluxes of conventional till and no-till.

atmospheric CO<sub>2</sub> concentration from the use of different agricultural practices. The C sequestration value alone pertains only to soil C stocks and is not representative of the effects of changes in agricultural practices on atmospheric CO<sub>2</sub>. Relative net C flux (Table 9) is a comparative value that indicates the net C flux of the new agronomic practice (NT) relative to the initial practice (CT). While net C flux indicates whether a system is a net contributor to atmospheric CO<sub>2</sub>, the relative net C flux shows the difference between two systems and the net benefit of changing from one system to another.

The potential for C sequestration in agricultural soils has been estimated here from a data base of 76 long-term experiments that considered the effects of tillage practices on SOC. This data base is being assembled by the Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSiTE), US Department of Energy. Preliminary analysis suggests that, on average, conversion from CT to NT in the US will result in sequestration of  $337 \pm 108$  kg C ha<sup>-1</sup> per year in agricultural soils, to a depth of 30 cm. The C sequestration potential for RT was insignificant and hence not used in this analysis. Kern and Johnson (1993) have also indicated the probability that RT does not enhance sequestration with respect to CT. A recent review of C sequestration as affected by soil management (Follett, 2001) indicates that C sequestration rates, with a change from CT to NT, could be 300–600 kg C ha<sup>-1</sup> per year in the US Great Plains and 100–500 kg C ha<sup>-1</sup> per year in the Cana-

dian prairie region. The CSiTE data base is global in scope and includes experiments in the US and Canada.

While SOC is expected to change in response to a change in management practices, the change will be finite and the concentration of SOC will approach a new steady state that is consistent with the new suite of management practices (Johnson et al., 1995). In this analysis, it was assumed that C sequestration could continue at an average rate of 337 kg C ha<sup>-1</sup> per year for 20 years following conversion from CT to NT. The rate of sequestration was assumed to then decline linearly for another 20 years, with SOC reaching a new steady state 40 years after conversion to NT (Lal et al., 1998).

The average net C flux when changing from CT to NT in the US (Table 9) was calculated by subtracting the average emissions from agricultural inputs and machinery (137 kg C ha<sup>-1</sup> per year) from the average C sequestration potential (337 kg C ha<sup>-1</sup> per year). Average emissions from inputs were calculated by averaging those from corn, soybean, and wheat crops (Table 8). These three crops together, and equally, constituted the majority (61% by area) of crops harvested in the US in 1996 (USDA, 1997a). The average net C flux, when continuing CT practices, is estimated at +168 kg C ha<sup>-1</sup> per year, a value that represents the annual emission of CO<sub>2</sub> from machinery and agricultural inputs. The net C flux following a change from CT to NT is estimated at -200 kg C ha<sup>-1</sup> per year. Thus, the total change in the flux of CO<sub>2</sub> to the atmosphere, following a change from CT to

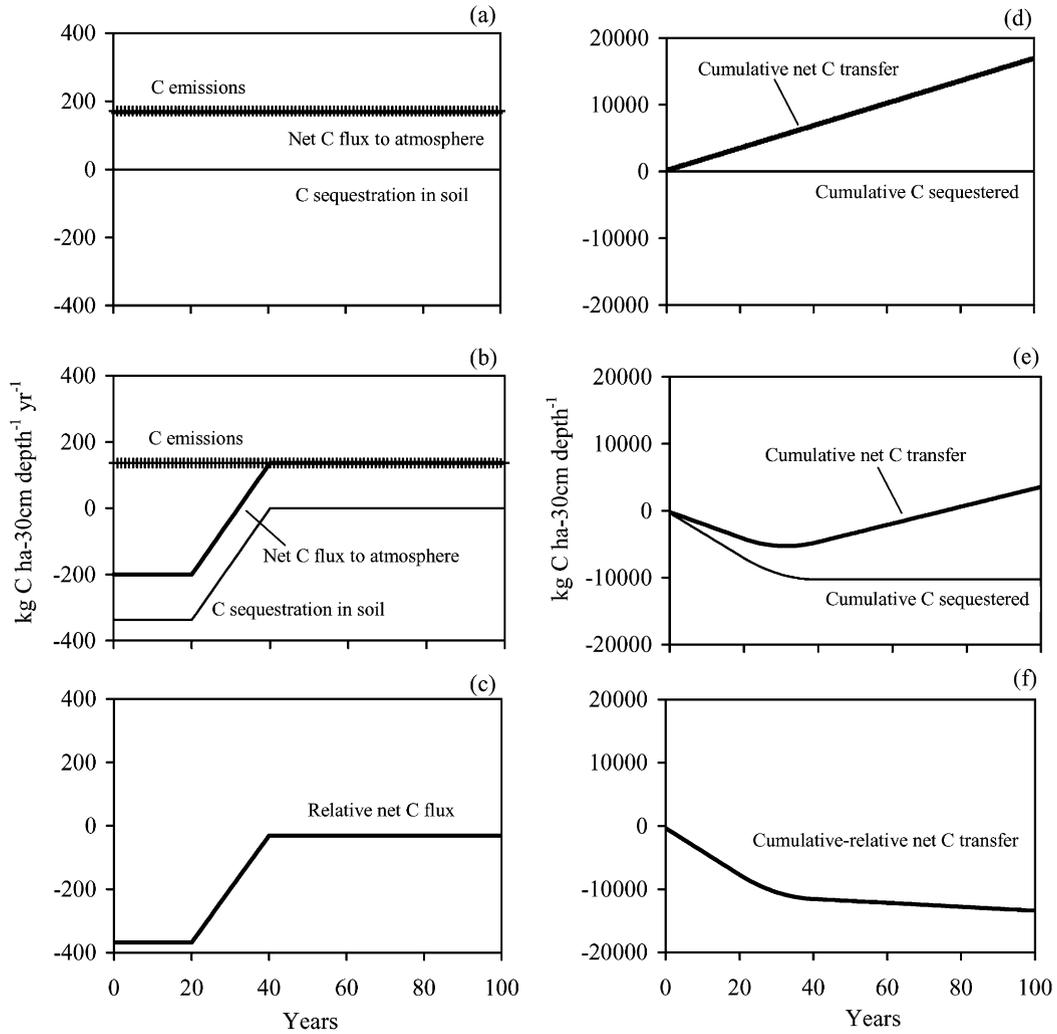


Fig. 2. Carbon dynamics for an average US crop changing from conventional tillage to no-till practices. Positive and negative values indicate CO<sub>2</sub> movement to and from the atmosphere, respectively. Annual soil C sequestration and net C flux (left) are shown for (a) continuation of CT; (b) following a change from CT to NT; and (c) the difference between net C flux for CT and NT. The cumulative amount of soil C sequestration and net C transferred between the soil and atmosphere (right) are shown for (d) continuation of CT; (e) following a change from CT to NT; and (f) the difference between the cumulative net C transfer for CT and NT. C emissions represent the rate of C emissions from fossil fuels used to run equipment and produce fertilizers and other agricultural inputs (see Fig. 1); C sequestration in soil refers to the reduction in atmospheric CO<sub>2</sub> caused by sequestering C in the soil; net C flux to the atmosphere is the combined impact on atmospheric C; cumulative net C transfer is the sum of annual net C flux over time; and the relative net C flux is the net C flux from CT subtracted from that of NT. CT and NT are conventional tillage and no-till, respectively. Initial C emissions and sequestration rates are from Table 9.

NT on non-irrigated crops, is expected to be about  $-368 \text{ kg C ha}^{-1}$  per year. This estimate is based on US national averages for CO<sub>2</sub> emissions from agriculture and the potential for C sequestration in soils (Table 9).

Given the estimates here of how the rate of C sequestration in soils will change with time and the expectation that the requirements for agricultural inputs will be maintained over time, the net C flux over time, as affected by a change in agricultural practices,

can be modeled (Fig. 2). Continuation of CT leads to a continuing annual flux of C to the atmosphere from agricultural operations (Fig. 2a), which results in a linear accumulation of net C transferred to the atmosphere (Fig. 2d). Following conversion from CT to NT, C emissions from agricultural operations are offset by C sequestration in soils and the net flux of C to the atmosphere is negative for 32 years (Fig. 2b). This results in a negative cumulative net C transfer for approximately 70 years (Fig. 2e). Additionally, the rate of C flux to the atmosphere under NT will always be less than that under CT, because the rate of fossil-fuel use for agricultural machinery and inputs has been reduced.

In order to calculate the overall benefit from changing tillage practices, C dynamics under NT should be compared to those under the original CT practices. The difference between tillage practices is given here as the relative net C flux rate (Fig. 2c) and the cumulative-relative net C transfer (Fig. 2f). Based on US average values, NT produces less CO<sub>2</sub> emissions than CT (Fig. 1). Since annual emissions will continue for as long as the adopted practice is continued, the continuing reduction in atmospheric CO<sub>2</sub> due to the change in tillage practice will be maintained indefinitely (Fig. 2f).

## 5. Discussion

Changes in tillage practice can lead to sequestration of C in agricultural soils (Kern and Johnson, 1993; Reeves, 1997; Smith et al., 1998). It is now widely advocated that sequestration of C in terrestrial ecosystems, including in agricultural soils, might be used to offset some of the emissions of CO<sub>2</sub> from burning fossil fuels (Intergovernmental Panel on Climate Change, 2000). However, changes in tillage practice generally imply a change in the use of fossil fuels in agriculture. Any effort to estimate the effect of changing tillage practice on the net flux of CO<sub>2</sub> to the atmosphere should consider both the C sequestered in soil and the emissions from fossil-fuel use in the affected system.

Kern and Johnson (1993) calculated average C emissions associated with crop production, based on an energy analysis by Frye (1984). Kern and Johnson estimated that C emissions associated with crop production using CT, RT, and NT were 52.8, 41.0,

and 29.0 kg C ha<sup>-1</sup> per year, respectively. Values estimated by Kern and Johnson closely resemble the estimates reported here for C emissions from agricultural machinery, averaged over corn, soybean, and wheat crops (Table 7), of 69.0, 42.2, and 23.3 kg C ha<sup>-1</sup> per year for CT, RT, and NT, respectively. The larger difference in the estimates for CT is due principally to the higher estimate in this analysis of fuel used in a moldboard plow operation. An estimate of all C emissions associated with crop production can be obtained by averaging the emissions associated with corn, wheat, and soybean production and including both the estimates from agricultural machinery and estimates for the production of agricultural inputs (Fig. 1). Average C emissions associated with the production of corn, wheat, and soybean in the US were estimated from this analysis to be 168, 146, and 137 kg C ha<sup>-1</sup> per year for CT, RT, and NT, respectively. These estimates, unlike those from Kern and Johnson, include the C emissions associated with the manufacture, transportation, and application of fertilizers, agricultural lime, and seeds. Follett (2001) further compares the estimates reported here for C emissions from machinery, fertilizers, and irrigation with estimates from other sources.

This analysis of available data on US agriculture suggests that, on average, a change from CT to NT will result in C sequestration in soil plus a savings in CO<sub>2</sub> emissions from energy use in agriculture. Considering both machinery and crop inputs (Fig. 1), NT generally contributes less C to the atmosphere than does CT. Results will vary on a regional and site-specific basis. For example, an average US continuous soybean crop, without irrigation, produces less CO<sub>2</sub> emissions from crop inputs when using CT than when using NT (Table 8). However, if the crop is irrigated, the NT practice produces less CO<sub>2</sub> emissions (Table 8).

The results calculated here for the average US agricultural crop would be far different for a change in practice that required an increase in fossil-fuel use to increase C sequestration. In a scenario where increased fossil-fuel use was necessary, part of the gain from sequestration would be negated by the increase in emissions. In the long term, the increase in fossil-fuel use could more than offset the amount of C sequestered in the soil. The effect of changes in fossil-fuel use is the dominant factor after year 40. The important point is that CO<sub>2</sub> emissions should be included in analyses

of C sequestration potential if the results are to be a basis for policies regarding C sequestration initiatives. Whereas C sequestration values indicate a change in the soil C stock, net C flux indicates the net impact on atmospheric CO<sub>2</sub>.

A comparison between tillage practices, and hence between net C flux estimates, necessitates calculations of relative net C fluxes. Absolute values of net C flux for specific tillage practices alone do not provide one with a measure of the benefit attained from changing practices. It should be noted, however, that agricultural land is not managed solely to sequester carbon; it is managed to produce agricultural crops. This analysis has produced an assessment of carbon fluxes per unit of land area, whereas it would be useful to have an assessment per unit of agricultural output. If a change in tillage practice results in a change in productivity, a change in the area being farmed would be required to maintain the same level of agricultural output. In essence this analysis assumes that the change from CT to NT is done in such a way as to maintain the initial level of productivity.

## 6. Conclusions

It is concluded from this full C cycle analysis on US agriculture that (1) on average, changing from CT to NT does not cause an increase in CO<sub>2</sub> emissions, and in most cases contributes to a decrease; (2) relative net C flux provides the best comparison between alternative agricultural practices in terms of contribution to the atmospheric CO<sub>2</sub> concentration; (3) changing from CT to NT in the US offers an opportunity to both increase C sequestration and simultaneously reduce C emissions from agriculture. Data sets presented here, along with the analytical framework, should be useful in examining other agricultural practices or site-specific projects.

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