Managing U.S. cropland to sequester carbon in soil

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The effects of human activities on atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) are under intensive study in the United States and worldwide. Since conversion to cropland during the 17th and 18th centuries, the vegetation and soils of the U.S. forests, grasslands, and wetlands have undergone extensive change. Clearing, tilling, and draining of these soils for long-term cropland use released large amounts of CO_2, a GHG, to the atmosphere from the soils' fertile soil organic matter (SOM). The SOM in topsoil often was depleted by up to half of its soil organic carbon (SOC) (Cambardella and Elliott 1992). Now, improved farming technologies, increased farmland productivity, and government programs to return highly erodible lands to permanent vegetation are producing unanticipated benefits by letting soils become major sinks for atmospheric CO_2 that is stored in them as increasing levels of SOC.

Estimates of total U.S. emissions of GHGs range from 1442 million metric tons of C equivalent (MMTCE), (DOE/EIA 1996), including 66 MMTCE from agricultural activities (Table 1), to 1666 MMTCE, including 80 MMTCE from agriculture (USEPA 1995). We estimate total U.S. emissions of 1600 MMTCE, including 109 MMTCE from agricultural activities (Table 2). Agriculture thus plays an important role in GHG emissions, however, agricultural lands can be a major sink with recommended management. With proper incentives and technologies, agricultural soils can sequester enormous amounts of CO_2 as SOC. U.S. agriculture can both sequester carbon (C) in soil and produce biomass fuel crops to substitute for fossil fuels, thereby offsetting other U.S. CO_2-C emissions.

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The overall contribution of U.S. cropland to radiative forcing resulting from CO_2 emissions from production inputs is small (Table 3). The direct input of fertilizers and pesticides is estimated at 12.9 MMTC and the indirect input of energy at 15.0 MMTC, or 27.9 MMTC total, and emission of CO_2-C by erosion at 15 MMTC (Table 4). The total CH_4 and N_2O from agricultural activities, the 15 MMTC by erosion, and the 27.9 MMTC of production energy input contribute about 7% of total U.S. emissions, regardless of whether the DOE/EIA (Table 1) or the USEPA estimates of total U.S. emissions are used. We estimate a total energy emission of 42.9 MMTC annually, which includes 15 MMTC/yr from erosion.

I. U.S. cropland

U.S. cropland area has been relatively constant during the 20th century—134 Mha in 1910, 152 Mha during World War I and II, 154 Mha during the export boom of the 1970s, and 134 Mha since the mid-1980s. The decrease in cropland area since the 1980s is partly due to diversions from production by federal farm programs (see section on CRP).

U.S. cropland is of five distinct types. (i) Harvested cropland consists of land used continuously for growing crops and from which crops are harvested; it constitutes 63% (84.4 Mha) of the total cropland. (ii) Cropland which was sown to crops but on which crops failed and were not harvested constitutes about 1% (1.3 Mha) of the total cropland. (iii) Cropland maintained as summer fallow constitutes about 7% (9.4 Mha) of the total cropland. (iv) Idle cropland, which includes land in cover and soil improvement crops or left completely idle for physical or economic reasons, constitutes about 15% (20.1 Mha) of the total cropland. (v) Cropland used for pastures grown in rotation with crops comprises 14% (18.8 Mha) of the total cropland. Judicious management of the last three categories of cropland, totaling 36% or 48.3 Mha, offers tremendous potential for C sequestration.

II. Soil organic carbon loss and stategies for mitigation

Uncultivated soils were in equilibrium with native vegetation cover and accumulated large SOC reserves, especially the soils in the northern U.S., which reached their pre-settlement level of SOC equilibrium after the last glaciation. Cultivation of these soils disrupted this steady state. Change in SOC content thereafter became a function of cultivation, erosion, and soil management (Rasmussen and Collins 1991). We estimate that U.S. cropland has lost about 5000 MMTC as a result of cultivation. The maximum potential for U.S. cropland to sequester C through adoption of recommended practices is likely in the range of 50 to 75% of the C lost or 2500 to 3500 MMTC, which may be reached over a 25- to 50-year period (Lal et al. 1998).

III. Strategies of C sequestration

U.S. agriculture provides four major ways to mitigate CO_2 emissions: (A) soil erosion management, (B) land conversion and restoration, (C) production of biofuels to off-set fossil fuel use, and (D) intensification of agricultural production on prime agricultural land.

A. Soil Erosion Management. A large proportion of SOC content is concentrated near the soil surface and therefore is highly vulnerable to mineralization processes associated with soil erosion. About 400 M m^3 of sediment are dredged each year to maintain and establish waterways and harbors.

While soil erosion may accelerate carbon emissions, sedimentation and downslope deposition may lead to deep burial of carbon or its translocation into lakes and oceans, where it may be sequestered over geological periods. On the whole, however, accelerated soil erosion exacerbates carbon emissions (Lal 1995, Paul et al 1997, Flach et al 1997). It is generally believed that 20% of the carbon dislocated by erosion may be released eventually into the atmosphere (Lal 1995).

The total suspended sediment transport in U.S. rivers was about 400 MMT/yr in the 1980s (Meade and Parker 1984). The load in 12 major U.S. rivers in 1991 was estimated at 336 MMT/yr for suspended load and 113.5 MMT/yr for dissolved load (Leeden et al. 1991). Assuming that 75% of the suspended load (mostly due to erosion) is contributed by cropland, sediment transport attributed to cropland

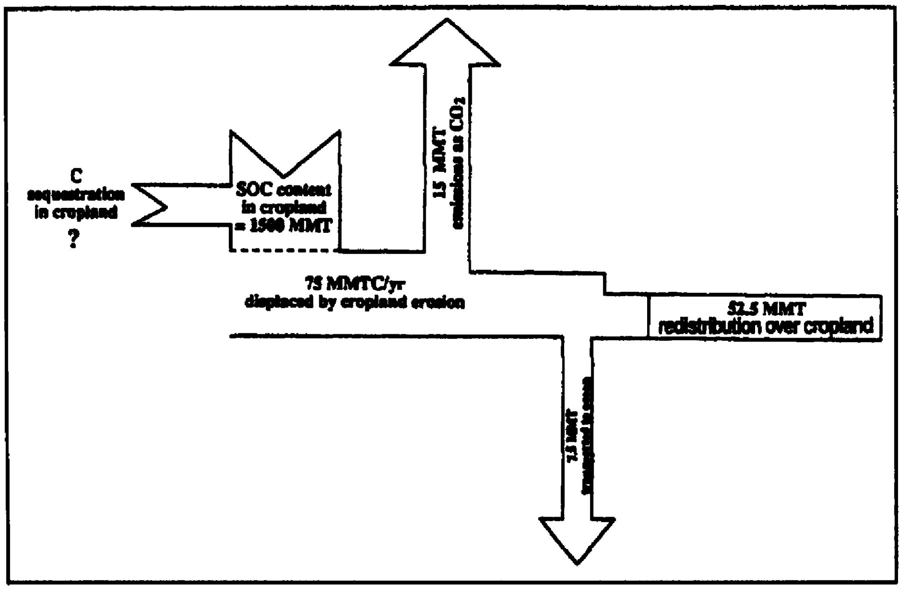

Figure 1. Soil erosion and C dynamics on U.S. cropland

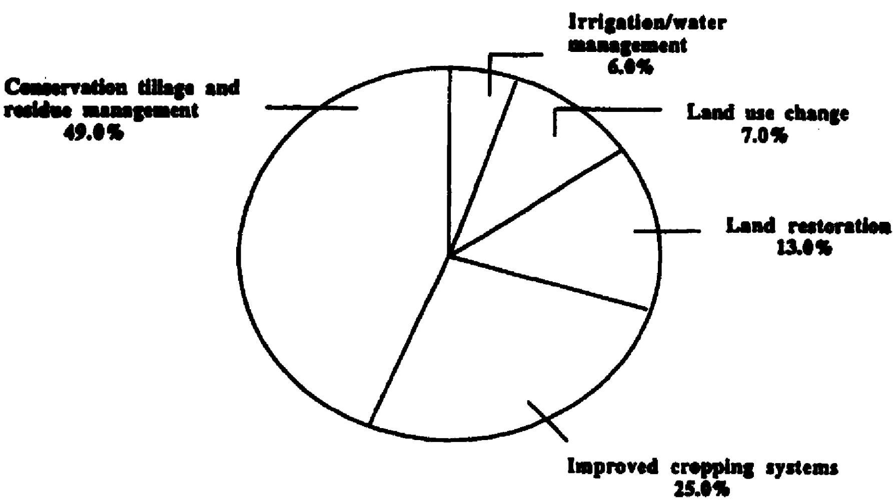

Figure 2. A pie diagram showing C sequestration potential of different components of improved management of U.S. cropland (see tables 6 and 7 for details)

is about 250 MMT/yr. Assuming a delivery ratio of 10% and SOC content of sediment of 3% (Lal et al. 1998), total SOC displaced by soil erosion from cropland is 75 MMT/yr (Figure 1). If 20% of the SOC displaced and redistributed over the landscape is mineralized, C exposed by disruption of aggregates is easily accessible to microorganisms, and the erosion-caused emission is about 15 MMTC/yr. The enrichment ratio, an important factor in these calculations, is rarely measured in plot or watershed experiments. Erosion-caused emission can be mitigated through adoption of effective erosion control measures.

B. Land conversion and restoration. The basic strategy in land conversion and restoration is to convert marginal agricultural land to non-agricultural restorative uses (e.g., grassland, forest, or wetland), restore lands drastically disturbed by different processes (e.g., erosion, salinization, fertility depletion), and restore wetlands and organic soils. Some of these lands can be used to produce biomass for conversion into biofuel.

1. Conversion of marginal land

a. Conservation Reserve Program (CRP). The CRP, as a provision of the 1985 and 1990 Farm Bills, was intended to convert highly erodible land (HEL) from active crop production to permanent vegetative cover for a 10-year period. The 1996 Farm Bill made major changes in the CRP—for example, it makes HEL, which best management practices (BMPs) cannot protect, targets for temporary land retirement. One of its objectives is to reduce transport of sediment and pollutants into natural waters.

Implementation of CRP leads to the sequestration of C into the soil and to soil erosion control. Follett (Follett 1993) estimated that about 13.8 Mha of CRP could sequester between 3 and 10 MMTC as SOC over 10 years. Paustian et al. (1995) estimated CRP would sequester about 25 MMTC in 10 years, with the rate of SOC accumulation ranging from <10 to more than 40 g C/m²/yr. Follett, Kimble, and co-workers have recently completed experimental measurements of average rates of SOC accumulation for paired CRP (average time of 7.9 years) and cropped soils across 14 sites in nine states in the Great Plains and Western Cornbelt. They observed average rates of SOC accumulation of 50 g c/m²/yr. ($P>001$; $t = 3.27$) in the 0-5 cm depth, 65 g c/m²/yr ($p>0.10$; $t = 1.92$) in the 0-10 cm. depth, and 100 g c/m²/yr ($p > 0.19$; $t = 2.12$) in the 0-20 cm depth. They also observed, after 7.9 yrs (average) for these same sites, that the average amount of SOC in CRP soils (0-10 cm depth) was about 75% of that observed in paired native grassland soils; whereas, the crop soils had an average of about 60% of that in the native grassland soils. A highly important reason associated with the increase in SOC may be soil erosion control (Osborn 1993).

b. Conservation buffers. Conservation buffers are vegetative filter strips used in conjunction with other recommended practices. Filter strips and riparian wetlands also can control flooding and minimize water pollution (Lant et al. 1995).

Vegetated strips, ranging from 5 to 50 m wide, usually are installed along streams and on HEL to minimize soil erosion and risks of transport of non-point source pollutants into streams. Such strips are called by different names, e.g., Filter Strips (6-30 m wide) to absorb run-on water and sediments from an upstream land, Riparian Buffers (15-45 m) established along a stream to absorb sediments and chemicals before the runoff enters a stream, and Grass Waterways (24-30 m) specifically designed for safe disposal of excess water from agricultural land.

The USDA has a program to encourage the development of 3.2 M km of Conservation Buffers by the year 2002. Assuming that an average width of all types of Conservation Buffers is 10 m, the total land area that would be covered by Conservation Buffers by the year 2020 is 3.2 Mha. Although it is likely higher, it is assumed that the average rate of C accumulation in Conservation Buffers is similar to that of the land under CRP, with a range of 30 to 70 g C/m²/yr and an average rate of 50 g C/m²/yr.

Table 1. Emission information about greenhouse gases, global and U.S. levels.

a. Global atmospheric concentrations, natural and anthropogenic sources, and absorption of three greenhouse gases

	Carbon Dioxide	Methane	Nitrous Oxide
Preindustrial atmospheric concentration (ppm)	278	0.700	0.275
1992 atmospheric concentration (ppm)	356	1.714	0.311
Average annual change (ppm)	1.6	0.008	0.0008
Average change per year (%)	0.4	0.6	0.25
Atmospheric lifetime (years)	50-200	12	120
Emissions from natural sources (MMT of gas)	550,000	110-210	6-12
Emissions from anthropenic sources (MMT of gas)	26,030	300-450	4-8
Absorption (MMT of gas)	564,670	460-660	13-20
Annual increase in the atmosphere (MMT of gas)	11,370-12,830	35-40	3-5
b. Emissions and global warming potential of three greenhouse gases from United States and U.S. farming activities			
Emissions from all United States sources (MMT of gas)	5287	31	0.471
Emissions from United States agriculture (MMT of gas)	157*	9	0.174
Global warming potential (100 years relative to CO_2)	1	21	310
Global warming potential from:			
Emissions from all United States sources (MMTCE)	1442	178	39
Emissions from United States agriculture (MMTCE)	42.9*	52	14

MMTCE = million metric tons of carbon equivalent
Data in Table 1 are adapted from DOE/EIA (3)
*As per calculations made in this report.

Table 2. Estimates of U.S. total and agricultural emissions

Estimated by	Total	Agriculture
	MMTCE/yr	
USEPA (3)	1666	80
DOE/EIA (1996)	1442	66
This report	1600	109

c. Restoring wetlands and restricting the use of organic soils. Wetlands are an important component of the overall environment. Approximately 15% of the world's wetlands occur in the U.S. (40 Mha), and nearly 30% of the nation's total wetlands are coastal (Rabenhorst 1995). Natural wetlands are reported to have a potential to accumulate peat at the rate of 25 to 43 g C/m²/yr (Mitsch and Wu 1995). Most data show that the net accumulation of C (peat accumulation minus CH_4 emission) in wetlands is about 25 g C/m²/yr, with a range of 15 to 35 g C/m²/yr.

A substantial conversion of natural wetlands to croplands and urban and other uses in the U.S. has occurred since the 1950s. While wetlands converted to agricultural land use (crops, pastures, and managed forests) can be restored through incentives and subsidies, those converted to urban and other uses cannot.

The Wetland Reserves Program (WRP) was established as a part of the 1990 Farm Bill to restore and protect wetlands that have been partially or fully converted to agricultural use. The WRP places accepted land areas under 30-year or permanent easements that prohibit draining. The program goal was to enroll about 0.4 Mha by 1995, and the expanded WRP envisages the introduction of 2 Mha of reserve wetlands, consisting primarily of drained bottomland previously planted to agricultural crops.

2. Restoration of degraded soils

(a) Eroded lands. U.S. cropland area subjected to moderate levels of wind and water erosion is estimated at 38.5 Mha, and that subjected to severe erosion is estimated at 6.3 Mha (Gomez 1995). Some of these lands are enrolled under the CRP estimated at 16.2 Mha, but some areas of moderately and severely eroded lands are not enrolled under CRP and can be diverted to soil restorative measures for C sequestration. Areas of such lands are estimated at 28.6 Mha (38.5 + 6.3 - 16.2 = 28.6Mha).

(b) Minelands and toxic soils. It is estimated that up to 0.63 Mha of stripmined land requires reclamation (Sutton and Dick 1987). Unreclaimed lands are prone to severe erosion, often 100 times more than the adjacent undisturbed lands. Reclaimed minelands can be used to grow row crops, pastures, and forests. Several studies have shown that applications of sludges and other amendments enable growth of crops, grasses, and other vegetation and lead to improvements in SOC contents (Schaller and Sutton 1978). Bennett (1977) reported, from an experiment in West Virginia with fertilizer and other management input, that SOC in a stripmined spoil was increased from 0.11 to 1.17% in the top 20 cm over a 4-year period. Some reclamative treatments may lead to substantial increase in SOC content (Peterson et al. 1982).

(c) Salt-affected soils. Irrigated cropland and pastureland in arid and semi-arid regions is prone to salinization. The total area of salt-affected soils in the U.S. is 19.6 Mha. Crop growth in severely salt-affected soils is poor. High salt content in soils can decrease biomass yield from 4% to 29%/mmho/cm, depending on the crop.

C. Creation of biofuels to offset fossil fuel. Biofuels, to be burnt directly without conversion into liquid biofuels, increasingly are recognized as a feasible alternative to fossil fuel (Giampietro et al. 1997), especially where large quantities of biomass are available for co-generation. Several options can increase production of biofuels, i.e., substituting them for other agricultural crops (e.g. those in surplus supply), growing forage crops and tree plantations as agroforestry systems, and growing biofuels as an integral component of soil and water conservation programs (e.g. buffer strips). Numerous species can be grown as biofuel crops (Cole et al. 1996). Trade-offs need to be worked out for site-specific situations considering production costs, harvesting, transporting and processing the biomass in large quantities.

Idle cropland constitutes about 15% of total cropland or about 20 Mha, and some of it could be used to produce dedicated biofuel crops. Assuming a net C assimilation rate of 5 T/ha/yr, 10 Mha will assimilate 50 MMTC/yr. With the energy substitution factor of 70% (0.7), the net energy saving may equal 35 MMTC/yr.

Whereas the above-ground 50 MMT/yr of biomass produced is used to generate biofuel offset at 35 MMTCE/yr, the below-ground biomass of about 50 MMT/yr would lead to enriched SOC content. At 40% C contained in the below ground biomass and with 20% efficiency (Giampietro and Pimentel 1997), the C sequestered in the soil is 4 MMTC/yr, with a range of 3 to 5 MMTC/yr.

D. Intensification of Agricultural Production on Prime Agricultural Land

Intensified production on prime agricultural land can be achieved through the widespread adoption of: (1) conservation tillage (CT), (2) management of crop residue and other organic material, (3) water management systems, including irrigation, drought management through runoff management and supplemental ir-

Table 3. Production Inputs—farm-energy uses directly into operating machinery and equipment on the farm and indirectly in fertilizers and pesticides produced off the farm

Farm Input	Quads	Joules*E15 kg times 1054	C/Joule*E9	MMTC
Fertilizer + Pesticides †	0.83 total *			
Nitrogen†	0.63	664.2	14.10 †	9.4
Phosphate †	0.06	63.24	15.74†	1.0
Potash†	0.05	52.7	17.10 †	0.9
Pesticides†	0.09	94.86	17.12 †	1.6
			Subtotal	12.9
Gasoline *	0.180	189.72	18.41 ‡	3.5
Diesel *	0.460	484.84	18.93 ‡	9.2
LP gas *	0.065	68.51	16.36 ‡	1.1
Natural Gas	0.085	89.59	13.78 ‡	1.2
			Subtotal	15.0
Total energy use				27.9

* Quads of energy interpolated from: Figure 3.3.1 (Production inputs — Energy) ERS. 1997, Agricultural Resources and Environmental Indicators, 1996-97. U.S. Department of Agriculture, Economic Research Service, Natural Resources and Environmental Division. Agricultural Handbook 712, and personal communication with Dr. M. Gill of USDA-ERS, Washington, D.C.
† Values estimated by R.F. Follett based upon partial energy input data in: Energy Use Survey, CY 1987. The Fertilizer Institute. 501 Second Street N.E., Washington D.C.
‡ Values based upon personal communication with Dr. Greg Marland (Oakridge National Laboratory, TN) and from: G. Marland and A.F. Turhollow, 1991. CO_2 emissions from the production and combustion of fuel ethanol from corn. Energy 16: 1307-1316.

Table 4. Soil erosion and C dynamics on U.S. cropland

Processes	Statistics	Total SOC (MMTC/yr)
1. Sediment transport by major rivers	336 MMT/yr	
a. Estimated contribution by cropland	75% or 250 MMT	
b. Sediment delivery ratio	10%	
c. SOC content in sediment	3%	
d. Total SOC displaced by erosion		75
2. Decomposition		
a. SOC displaced—biodegraded, mineralized, and released as CO_2	20%	15
b. C relocated over the landscape	70%	52.5
3. Sediment transport to the ocean from cropland		
a. Total sediments	250 MMT/yr	
b. SOC transported to the ocean		7.5
4. Total runoff		
a. Runoff volume	$50 \times 10^9 m^3$	0.3
b. Organic C in runoff	(6 mg/L)	

Sediment transport data from Meade and Parker (1984); Leeden et al. (1991). For SOC content, see Lal (1995a).

rigation, and water table management of seasonally wet lands to improve soil aeration and infiltration capacity, and (4) adoption of improved cropping systems.

1. Conservation Tillage and Residue Management

(a) Conservation tillage. About 37% of the land farmed in the U.S. is now managed with a CT system. Of the 119.2 Mha of cropland in 1997, 44.4 Mha used some form of CT, including no till, minimum till, or ridge till (CTIC 1997). Schertz (1988) estimated that approximately 48% of arable land in the southeastern U.S. is managed under some form of CT, and the area may increase to 65% by the year 2000.

Long-term use of a CT system leads to an increase in SOC content, enhancement of soil quality, and improvement in soil resilience (Grant 1997). Intensive tillage, especially plowing, accentuates C oxidation by increasing soil aeration and soil residue contact, and accelerates soil erosion by increasing exposure to wind and rain (Grant 1997). In contrast, CT can improve soil aggregation and change the vertical distribution and retention of SOC content. Several experiments have shown more SOC content in soils of CT, compared with plow till seedbed preparation (Cambardella and Elliott 1992, Kern and Johnson 1993, Reicosky et al. 1995). Increased SOC content also leads to improvement in soil structure and aggregation under CT, compared with plow till.

A summary of the available literature indicates that the SOC sequestration potential of conversion to CT ranges from 0.1 to 0.5 MT/ha/yr for humid temperate regions and from 0.05 to 0.2 MT/ha/yr for semi-arid and tropical regions (Paustian et al. 1997). Energy savings also occur with adoption of a CT system. Kern and Johnson (1993) estimated that fossil fuel emissions from field manipulations and herbicide production are 53 kg C/ha/yr for plow till, 45 kg C/ha/yr for minimum till, and 29 kg C/ha/yr for no till.

Estimates of C sequestration potential of adopting CT vary widely. Kern and Johnson (1993) estimated that adoption of CT on 75% of U.S. cropland by 2020 would result in total C sequestration in soils from 80 to 129 MMT. Lal (1997) estimated that adoption of CT in the U.S. has a total C sequestration potential of 350 MMTC to 1400 MMTC by the year 2020.

(b) Crop Residues and Other Biomass Management. The SOC pool is a function of the quantity of crop residue, plant roots, and other organic material returned to the soil and the rate of their decomposition. The increase in SOC content through crop residue application depends on the quantity and quality of the residue, soil properties, and management. Within a cropping/farming system, the equilibrium level of SOC content often is related linearly to the amount of crop residue applied to the soil. Paustian et al. (1992) observed that lignin content of the residue has a strong positive effect on SOC accumulation.

There are several estimates of crop residue production in the U.S. The total is about 1118 MMT, which includes total above-ground residues (508 MMT) and below-ground biomass plus weeds (610 MMT) (Table 5). These estimates are based on the available information, and may be improved with additional research data. It is assumed that 50% of the residue produced is used as mulch with conversion to CT. Potentially the remaining 50% can be sequestered as SOC. The average C content of crop residues is about 40%. Assuming that 10% of the C contained in 50% of the crop residues can be sequestered as humus, the C sequestration potential of crop residues is 22.5 MMTC/yr.

There is another option for using 50% of this crop residue. Assuming that one-fourth of the total above-ground residue produced can be used for direct biofuel purposes, the net C amount in 127 MMT of crop residue is 50 MMT. Realization of this option depends on several site-specific factors, including the economics. With an energy substitution factor of 0.6 to 0.7, C emission reduction through the use of 25% of the crop residue as biofuel is 30 to 35 MMTC/yr. If this were the option,

Table 5. Estimation of total C produced in crop residue in the United States

Crop	Crop (1) Category	Area plntd in 1996 (2)(3) 1000 acs	1000 ha	US total above-ground crop residue weight (4) 1000 tons	tons/ha	Residue Carbon (5) above grnd MMTC	root & weed MMTC	Total (6) Residue C MMTC
Corn	1	88628	35868	245345	6.84	98.138	117.766	215.904
Sorghum	2	15526	6283	23264	3.70	9.306	11.167	20.473
Soybeans	3	60826	24616	84412	3.43	33.765	40.518	74.282
Cotton	4	14249	5767	4220	0.73	1.688	2.025	3.713
Wheat	6	74611	30195	106587	3.53	42.635	51.162	93.797
Barley	7	7110	2877	12769	4.44	5.108	6.129	11.237
Rice	—	3000	1214	7755	6.39	3.102	3.722	6.824
Other row	5	12566	5085	10278	2.02	4.111	4.934	9.045
Other field	8	16687	6753	13649	2.02	5.460	6.551	12.011
Totals		293203	118659	508279		203.312	243.974	447.286

(1) USDA (1997)
(2) CTIC (1997). 1996 total planted acres from CTIC web site, individual crop acres based on % of acres for crop categories 1-5 from ref (1). Rice acres estimated to have increased from 2,857 acres and from 5,617 lbs/ac ave yields reported by the USDA (1991).
(3) USDA (1978). Other row and other field crop acres from USDA (1987), their percent of the total residue production of the other categories plus rice is based upon the same percentage that was calculated from data reported in USDA 1978. Improving soils with organic wastes.
(4) The ratios of residue weight to harvested crop were obtained from Larson et al. (1978), Larson et al. (1983), and Banerjee et al. (1990).
(5) This assumes that all residues (i.e. above ground, below ground, and weeds) are 40% C by weight. A multiplier factor of 2.2, based on wheat/fallow data (Follett et al. 1997) was used to estimate the weight of weeds plus roots.
(6) The residue C produced = 1,118,214,000*0.40 or 447,286,000 tonnes of residue C.
Note #1 Calculation of total above-ground crop residue produced for 1996 is 508,279 thousand tons compared to 1978 production of 391,009 thousand tons reported by USDA (1978).
Note #2 The residue C produced is calculated as 447,286,000 tons of residue C produced on 118,659,300 ha. Thus, the overall average C produced/ha is 3.77 tons C/ha/yr.
Note #3 The efficiency of incorporation of residue C is calculated as weight of C sequestered divided by tons weight of residue C returned to the soil. It was assumed that the percent of C sequestered into soil organic C was the same for all crop types.
Note #4 Follett et al. (1997) reported the efficiency of incorporation of total residue C was 5.4% when measured in an 84 year study at Akron, CO and 10.5% when measured in a 20 year study at Sidney, NE. Both studies were with wheat-fallow. For a 5 or 10% C sequestration efficiency, amounts of total residue C sequestered would be 447,286,000 times 0.05 or 0.10 or 22,364,300 and 44,728,600 tons residue C, respectively.

the amount of C sequestration in soil would be reduced by 50% to 11.2 MMTC/yr.

2. Irrigation water management

(a) Surface irrigation. Surface irrigation is used on some 21 Mha of cropland. Irrigation of drought-prone soils can enhance SOC content. In Wyoming, Mayland (1961) reported that the SOC content of irrigated soils differed among crop rotations and nutrient management techniques. He observed that, for the 40-year period from 1917 to 1956, the SOC content of the 0-20 cm layer was 2.0% for corn-wheat-oats rotation with manure, 1.35% for corn-wheat-oats without manure, and 0.82% for continuous corn. Experimental data quantifying the impact of irrigation on SOC dynamics are scanty, and this topic is a researchable priority. Data from Nebraska showed that irrigated soil gained C at the rate of 1.66 Mg/ha 30 cm over a 15-year period (Leuking and Schepers 1985). Therefore, the rate of SOC sequestration in this irrigated soil was 110 kg/ha/yr 30 cm. Because of a wide range of soils, climate, cropping systems, and fertility management practices, we can justifiably assume that although there can be exceptions, conversion of dryland farming to irrigated agriculture may increase SOC content in the soil profile by 50 to 150 kg/ha/yr, with an average rate of 100 kg/ha/yr.

Some calciferous irrigated soils also contain large concentrations of calcium carbonate ($CaCO_3$) or soil inorganic carbon content, as much as 1.2 Mg C/ha 10 cm of soil depth for each 1% of $CaCO_3$ present. Irrigation of soils in arid and semi-arid regions also affects the SOC pool and its dynamics. This is a complex issue, and all interacting processes involved are not clearly understood, especially with regard to solubilization of secondary carbonates, e.g., $CaCO_3$.

(b) Sub-irrigation on poorly drained soils. Providing drainage to seasonally wet lands improves aeration and enhances mineralization of SOC content. Considerable areas of seasonally wet soils have been drained by installing surface or sub-surface drainage. In Ohio, Fausey and Lal (1992) observed that drained soil had lower SOC content than undrained soil for all tillage methods. The loss of SOC due to drainage in the top 50-cm depth was 36.4% for no till, 23.3% for raised beds, 40.0% for ridge till, and 33.3% for moldboard plow. The average loss, mean of all tillage methods, was 33.3%.

Improved management of such lands may restore SOC content, such as does conversion from a conventional to a CT system. Drained agricultural lands are better managed through CT or through a sub-irrigation system, which involves recycling the drained water during summer. Experimental data quantifying the impact of improved water table management on SOC dynamics are not available.

3. Improved cropping systems ***(a) Fertilizer management.*** Several experiments have shown that additions of fertilizers on a regular basis for many years often leads to an increase in SOC content. Paustian et al. (1992) reported that fertilizer N addition increased the SOC level by 15 to 19% by increasing net primary productivity (NPP) and the residue-C input. In southwestern Saskatchewan, Campbell and Zentner (1993) observed a strong positive correlation between soil organic nitrogen and the quantity of crop residues returned, and a strong negative correlation with apparent N deficit (e.g., N exported in grain-N applied as fertilizer). Franzluebbers et al. (1994) observed that the SOC content of the 0- to 50-mm depth was 62% more in wheat cultivation with fertilization than without. Robinson et al. (1996) observed a 22% increase in SOC content due to application of NPK fertilizer to a soil in Iowa. Gregorich et al. (1996) observed that soil under continuous corn, fertilized for more than 30

Table 6. Estimates of C sequestration potential through improved management of U.S. cropland

Scenario (MMTC/yr)	Area (10^6 ha)	C sequestration potential (MTC/ha/yr)	Total potential (MMTC/yr)	Sum
A. Land Conversion and Restoration				
1. Land Use				6-14
(i) Conservation Reserve Program	16.2	0.3-0.7	5-11	
(ii) Conservation Buffers	3.2	0.3-0.7	1-2	
(iii) Wetland Reserve Program	2.0	0.15-0.35	0.3-0.7	
2. Land/Soil Restoration				11-25
(i) Eroded lands	28.6	0.3-0.7	9-20	
(ii) Mine lands	0.63	1-3	0.6-2	
(iii) Salt affected soils	19.6	0.05-0.15	1-3	
B. Intensification of Prime Agricultural Land				
3. Conservation Tillage and Residue Management				35-107
(i) Conservation tillage	100	0.24-0.40	24-40	
(ii) Residue management	—	—	11-67	
4. Irrigation Water Management				5-11
(i) Supplemental	21	0.1-0.3	2-6	
(ii) Sub-irrigation	43.4	0.7-0.12	3.5	
5. Improved Cropping Systems				19-52
(i) Fertilizer management	117.5	0.5-0.15	6-18	
(ii) Organic manures and by-products	—	—	3-9	
(iii) Rotation with winter cover crops	51	0.1-0.3	5-15	
(iv) Summer fallow elimination	9.4	0.1-0.3	1-3	
(v) Improvement in crop yields	117.5	0.004-0.006	0.5-07	
(vi) Management of rice straw	1.3	0.4-1.15	0.5-1.5	
(vii) Idle land management	20	0.15-0.25	3-5	
Total Potential				75-208

Total potential = area x rate of sequestration

years, had greater amounts of SOC than unfertilized systems.

The long-term experiment on the Sanborn plots at Columbia, Missouri, highlights the importance of soil fertility management on SOC content. Anderson et al. (1990) observed that, following 100 years of continuous cropping, SOC contents in unfertilized versus fertilized plots were, respectively, 0.9% and 1.3% under wheat, 0.7% and 1.4% under corn, 1.3% and 2.1% under timothy, and 0.9% and 1.3% under rotation.

The net U.S. cropland area that receives chemical fertilizers and organic amendments is about 117.5 Mha, most of which is receiving adequate rates of fertilizers. Nonetheless, soil and crop management practices, better use of soil-test information, applications of fertilizers on a site-specific basis, and use of precision farming techniques can make fertilizer use far more efficient (Larson and Robert 1991). Recently, Halvorson et al. (1999) have reported an annual increase in SOC of between 134 to 182 kg/ha/yr depending upon the N-fertilizer rate (67 or 134 kg N/ha) after 11 crops. Assuming that improved soil fertility management practices can enhance SOC content at a rate of 50 to 150 kg/ha/yr with an average rate of 100 kg/ha/yr, the C sequestration potential through soil fertility management on cropland is 11.8 MMTC/yr.

(b) Organic manures and by-products. The U.S. produces a large amount of a wide range of organic materials, including livestock wastes, biosolids (sewage sludge) and septage, food processing wastes, industrial organic wastes, logging residues, wood processing wastes, and yard clippings. Agricultural composting is also increasing in the U.S., and these anaerobically digested biosolids contain considerable quantities of plant nutrients. Judiciously applied to cropland, these wastes are a valuable source for plant nutrients and C.

Walker et al. (1997) estimated that, of the more than 1000 MMT of organic and inorganic agriculturally recyclable byproducts generated each year in the United States, about 40% (400 MMT) are crop residues, 5% dairy and beef manures (50 MMT), 3% poultry and swine manure (30 MMT), 15% municipal solid waste (150 MMT), and less than 1% (<10 MMT) biosolids. The municipal solid waste of organic origin is about 55 MMT/yr, including wood (11.2 MMT), food waste (12.0 MMT), and yard trimmings (31.8 MMT) (USDA 1993). In addition to crop residue, the total organic material available for disposal on agricultural soils is about 145 MMT, containing about 58 MMTC.

(c) Rotation and winter cover crops. The effects of crop rotation on SOC content, based on growing winter cover crops, have been documented widely in numerous long-term experiments conducted throughout the United States (Campbell and Zentner 1993, Robinson et al. 1996, Wood et al. 1991a, Wood et al. 1991b, Collins et al. 1992, Robinson et al. 1996a, Hu et al. 1997). Angers (1992) observed that SOC content under alfalfa increased from 2.6% to 3.0% over a 5-year period. However, the magnitude of increase may be small in some instances and varies among soils, ecoregions, cover crops, and rotations.

Winter cover crops can be grown in 26 states for cropland areas sown to corn and soybeans. Since winter wheat is itself a winter cover crop, the land in winter wheat cannot be sown to a different cover crop. Therefore, land area suitable for adopting improved cropping systems based on rotation with a winter cover crop is about 51 Mha.

(d) Elimination of summer fallow. Summer fallowing often is practiced in semi-arid regions. Land under summer fallow in the United States totals 9.4 Mha, or 7% of the total cropland. Summer fallowing reduces SOC content by decreasing inputs of plant residues, increasing decomposition rates, and increasing soil erosion (Campbell et al. 1991, Havlin et al. 1990). Angers (1992) reported that a fallow-based system resulted in a net SOC loss. Wood et al. (1991a, 1991b) observed that a wheat-fallow system for a 4-year period resulted in a loss of 620 kg/ha of SOC. Summer fallow, however, can be advantageous in some site-specific situations.

Replacement of a fallow system with intensive cropping increased SOC content (Wood et al. 1991a, Wood et al. 1991b, Collins et al. 1992). Bremer et al. (1995) observed that, over a 25-year period, SOC

Table 7. The overall potential of U.S. cropland for C sequestration and fossil fuel off-set and erosion control

Scenario	Carbon sequestration/fossil fuel off-set MMTC/yr
1. C sequestration in soil	75-208
2. Carbon off-set through biofuel production	35-63
3. Saving in fuel consumption by CT	1-2
4. Reduction of C emission from eroded sediments	12-22
Total	123-295

content in the 0- to 15-cm depth was 11% higher in continuous wheat than in wheat-fallow rotation. Grant (1997) observed that, during a 14-year simulation of a field experiment in a semi-arid environment, 18 to 20 g/m^2/yr more of C would be sequestered in the upper 0.15 m of soil in continuous wheat than in a wheat fallow system.

(e) Improvement in crop yields. Because of the increasing demand for food grains and oil seeds throughout the world, it is likely that crop yields in the U.S. will continue to increase. The rate of increase may be 1.4%/yr for the 30-year period between 1990 and 2010 (Flach et al. 1997). The increase in yield may be due to varietal improvement, efficient use of fertilizer and pesticides through site-specific management, widespread adoption of IPM, and other advances in biotechnology. Increases in crop yield also may lead to corresponding increases in crop residue and biomass that may be returned to the soil.

The additional rate of residue C produced will be 5 to 7 MMTC/yr with an average of 6 MMTC/yr. Assuming that 5 to 15% (average 10%) of this C is sequestered in soil through adoption of BMPs, the rate of C sequestration is 0.6 MMTC/yr.

(f) Management of rice paddies. Land area used for rice cultivation in the U.S. is about 1.3 Mha, which is 0.7% of the world rice area and less than 1% of the U.S. cropland. Rice is grown in two geographical regions of the country, the lower Mississippi River valley (Arkansas and Mississippi) and the Sacramento River Valley (California). Total rice production in the U.S. is 7.9 MMT (FAO 1995), and total rice straw production is estimated at 12.5 MMT, which contains about 5 MMT of C. Improved management of this straw (through compost and mulch farming rather than burning) may lead to C sequestration at the rate of 0.5 to 1 MMTC/yr. This potential needs to be exploited through development of appropriate techniques.

IV. Overall potential of U.S. cropland to mitigate greenhouse effect

Properly managed, U.S. cropland can be a major sink for C sequestration (Table 6). The total C sequestration potential of 75-208 MMTC/yr represents a large sink in comparison with total U.S. emissions of GHGs in the range of 1442 MMTCE (9.8%) or 1666 MMTCE (8.5%). The total SOC sequestration potential is 1.30 times the emission from all agricultural activities, which is estimated at 109 MMTC/yr.

Management strategies with large potentials for C sequestration are erosion prevention and control through conservation tillage and residue management (49%), improved cropping systems (25%), land restoration (13%), land conversion (7%), and irrigation and water management (6%) (Figure 2). This potential can be realized through appropriate policies that encourage farmers to adopt improved soil, crop, and water management practices.

The data in Table 7 present an overall summary of the potential of U.S. cropland for C sequestration in soil, fossil fuel offset, and savings in energy due to adoption of conservation tillage. In addition to the C sequestration potential of 75-208 MMTC/yr, fossil fuel offset through production of biofuel is estimated at 35-63 MMTC/yr. There is also a savings of fuel consumption equivalent of 1-2 MMTC/yr due to conversion from plow till to the no till method of seedbed preparation. Effective control of soil erosion can curtail C emission from displaced sediment estimated at 12-22 MMTC/yr. The overall potential of U.S. cropland for CO_2 mitigation thus is 123 to 295 MMTC/yr.

The quantity of carbon sequestration in soil has a practical upper limit. In addition, achieving this limit may require at least 50 years. In contrast, C offset through biofuel production and C accumulation in wetlands, in principle, can be maintained indefinitely. Thus, the maximum potential for C sequestration of 5000 MMT may not be realized until after 2050. Realizing this potential depends on identifying relevant policies, developing appropriate programs, and successfully implementing the policies and programs.

V. Summary

Present agriculture contributes significantly to environmental issues, especially those related to water contamination and the greenhouse effect. The data presented herein amply demonstrate, however, that scientific agriculture can also provide solutions to these environmental issues in general and to mitigating the greenhouse effect in particular. In fact, agricultural practices sequester more C in soil than farming emits through land use and fossil fuel combustion.

This points to another important criterion that must be considered in evaluating agricultural sustainability: the effectiveness and efficiency of agricultural practices in sequestering C in soil. Sustainable agricultural systems thus involve those soil, crop, and water management techniques that increase productivity while enhancing C sequestration in soil — crop residue management, conservation tillage, nutrient management, site-specific farming, water management involving drainage and irrigation, and restoration of degraded soils through CRP/WRP, afforestation, and other proven technologies.

By adopting a holistic approach and identifying and implementing appropriate policies, we can realize the vast potential of U.S. cropland to mitigate the greenhouse effect at the rate of 123-295 MMTC/yr. The net gain in C through adoption of recommended agricultural practices is 100 MMTC/yr (209 MMT/yr gain - 109 MMT/yr emissions).

Like the other components of an ecosystem (Costanza et al. 1997), SOC is a valued commodity. There is a need to develop criteria for assessing the economic worth of SOC. The economic value of SOC may depend on several on-site (benefits to farmer) and off-site or societal benefits. Furthermore, the value of C in SOC vis-a-vis that in the biomass must also consider the decomposition fraction. Only 10 to 20% of the C in the biomass may be converted to SOC content. Some agronomists estimate the value of plant nutrients and available water in SOC at about $0.20/kg or $200/MT. It is also estimated that reduction in C emissions at national scales would require a carbon tax ranging from $50 to $350/MT of C (OECD 1994). Assuming a tax credit of $50/MT, net saving of 100 MMTC/yr amounts to $25 billion/yr or $96/capita/yr.

ACKNOWLEDGMENT

This paper is condensed from the book The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. *Publisher: Sleeping Bear Press.*

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