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Soil management concepts and carbon sequestration zin cropland soils

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Abstract

One of the most important terrestrial pools for carbon (C) storage and exchange with atmospheric CO_2 is soil organic carbon (SOC). Following the advent of large-scale cultivation, this long-term balance was disrupted and increased amounts of SOC were exposed to oxidation and loss as atmospheric CO_2. The result was a dramatic decrease in SOC. If amounts of C entering the soil exceed that lost to the atmosphere by oxidation, SOC increases. Such an increase can result from practices that include improved: (1) tillage management and cropping systems, (2) management to increase amount of land cover, and (3) efficient use of production inputs, e.g. nutrients and water. Among the most important contributors is conservation tillage (i.e., no-till, ridge-till, and mulch-tillage) whereby higher levels of residue cover are maintained than for conventional-tillage. Gains in amount of land area under conservation tillage between 1989 and 1998 are encouraging because of their contributions to soil and water conservation and for their potential to sequester SOC. Other important contributors are crop residue and biomass management and fallow reduction. Collectively, tillage management and cropping systems in the US are estimated to have the potential to sequester 30–105 million metric tons of carbon (MMTC) yr^{-1}. Two important examples of management strategies whereby land cover is increased include crop rotations with winter cover crops and the conservation reserve program (CRP). Such practices enhance SOC sequestration by increasing the amount and time during which the land is covered by growing plants. Crop rotations, winter cover crops, and the CRP combined have the potential to sequester 14–29 MMTC yr^{-1}. Biomass production is increased by efficient use of production inputs. Optimum fertility levels and water availability in soils can directly affect quantity of crop residues produced for return to the soil and for SOC sequestration. Nutrient inputs and supplemental irrigation are estimated to have the potential to sequester 11–30 MMTC yr^{-1}. In the future, it is important to acquire an improved understanding of SOC sequestration processes, the ability to make quantitative estimates of rates of SOC sequestration, and technology to enhance these rates in an energy- and input-efficient manner. Adoption of improved tillage practices and cropping systems, increased land cover, and efficient use of nutrient and water inputs are examples where such information is necessary. Published by Elsevier Science B.V.

Keywords: Conservation tillage; Residue management; Carbon; Soil organic carbon; C-sequestration; Soil fertility; Irrigation; Energy use; C-emissions from agriculture

1. Introduction

Improved agricultural practices have great potential to increase the amount of carbon (C) sequestered in cropland soils. By the adoption of recommended management practices (RMPs), agriculture contributes not only to soil conservation and water quality goals, but also for enhancing the amount of soil organic carbon (SOC) in the soil and to mitigating carbon dioxide (CO_2) emission effects on climate change. However, the public, policy makers, and

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politicians are insufficiently aware of this potential. The term "climate change" raises the concerns of some that it is a threat, while others are skeptical that it is real. Climate change refers to long-term alterations in temperature, precipitation, wind, and other elements of the Earth's climate system. Natural processes such as solar-irradiance variations, deviation in the Earth's orbital parameters, and volcanic activity can cause fluctuations in climate (IPCC, 1996). The climate system is also influenced by the concentrations of various atmospheric gases, some of which contribute to the phenomenon of global warming. These gases are called "greenhouse gases" (GHGs). The GHGs can absorb heat, much as greenhouse glass does, and restrict absorbed heat from reflecting back to outer space. Because of this capacity of GHGs to trap solar heat, climatologists and others are concerned about global temperatures which will increase at a more rapid rate than the World can adjust to. Global warming, including the contributions by GHGs, is important because without global warming, estimates of the Earth's temperature would be about 34°C lower (IPCC, 1996). Naturally occurring GHGs include water vapor, CO_2, methane (CH_4), and nitrous oxide (N_2O). The 1996 report of the International Panel on Climate Change (IPCC) states that there is "clear evidence that human activities have affected concentrations, distributions and life cycles of these gases" (IPCC, 1996). Since about 1750, the concentrations of CO_2, CH_4 and N_2O in the atmosphere have increased by 30, 145 and 13%, respectively (Table 1). The global warming potential (GWP) of each of these gases are expressed relative to that of CO_2, which has a value of 1, and CH_4 and N_2O are 21 and 310, respectively. With CO_2 as the reference gas, emissions of each GHG are weighted such that all are measured in million metric tons of carbon equivalents (MMTCE). Table 1 shows the rates of GHG emissions by all US sources and by US agriculture. Agricultural activities contribute CO_2 emissions to the atmosphere from fossil-fuel combustion, farm chemical manufacture, soil erosion processes, and the loss of native soil organic matter (SOM). Lal et al. (1998) made estimates that CO_2 emissions for US agriculture are about 42.9 MMTC yr^{-1}.

Although CH_4 and N_2O need to be considered, the focus of this paper is on the issues associated with CO_2. Long-term measurements of the increasing concentration of atmospheric CO_2 (Table 1) show that the atmospheric CO_2 concentration has increased to about 370 ppm, primarily during the last half of the 20th century. After remaining near 270–290 ppm during the past several thousand years, this increase was coincident with the rapid rise of fossil-fuel burning during the same period (Sarmiento and Wofsy, 1999). Although there is no consensus as to how much change will occur, there is general agreement that it is worthwhile to reduce GHG emissions to decrease the risks that many scientists feel are associated with climate change.

In terrestrial ecosystems, SOC is the largest pool and globally contains over 1550 Pg C followed by the soil inorganic carbon (SIC) pool that contains 750–950 Pg C (Batjes, 1996; Eswaran et al., 1993; Schlesinger, 1995). A Pg is equal to 10^{15} g or 1000 million metric tons (MMT). Terrestrial vegetation is reported to contain an additional 600 Pg C (Houghton, 1995; Schimel, 1995). Thus, the soil C pool (SOC plus

Table 1
United States and agricultural emissions of three GHGs

	Carbon dioxide	Methane	Nitrous oxide
Pre-industrial atmospheric concentrations (ppm)	270–290[a]	0.007	0.275
Increase since 1750 (pre-industrial) concentrations (%)	30	145	13
1998 atmospheric concentrations (ppm)	370[a]	1.714	0.311
GWP (100 year time horizon)[b]	1	21	310
All United States sources (MMTCE yr^{-1} 1997 data)[b]	1488	180	109
Emissions from United States agriculture	42.9[c]	54[b]	77[b]

[a] Sarmiento and Wofsy, 1999.

[b] USEPA, 1999.

[c] Lal et al., 1998; USDA, 1997a. The 42.9 MMTC yr^{-1} includes 27.9 MMTC yr^{-1} from production energy inputs and farm energy use plus 15 MMTC yr^{-1} resulting from CO_2 emissions associated with soil erosion.

SIC) is about four times larger than the terrestrial vegetation pool and three times larger than the atmospheric C pool. The locations of the soil-C pools extends across the land surfaces of the Earth. The net annual increase in atmospheric CO_2-C is estimated to be about 3.3 Pg yr^{-1} (Sarmiento and Wofsy, 1999). Consequently, even a small annual percent change in the amount of C stored or released from these large terrestrial C stocks could easily affect the net change in atmospheric-CO_2.

2. Carbon sequestration

SOC levels in soils reflect the long-term balance between additions and losses of organic carbon. Following the advent of large-scale soil cultivation, this long-term balance was disrupted and more and more of the C in the soil's organic matter was exposed to oxidative processes through continued cultivation. About 20% of the earth's land area is used for growing crops (Allmaras et al., 1999) and thus farming practices have a major influence on C stored in soil and released into the atmosphere as CO_2. Until recently in the US, farming practices resulted in a dramatic decrease in the SOC as more and more of the C in the soil was oxidized. The SOC decreased until a new balance was approached (Fig. 1) because it had become more available to living soil organisms that not only continually respire the C back to the atmosphere as CO_2, but also release the nutrients in the SOM. Thus, cultivation is in fact a form of ''mining'' soil nutrients to make them rapidly available for plant uptake, but unfortunately also making them vulnerable to losses into the environment. If amounts of C entering the soil exceed that lost to the atmosphere and oxidative processes are slowed by management changes to retain more crop residues on or near the soil surface, these processes can be reversed and the SOC increased (Fig. 2). Such changes can result from the adoption of less-aggressive tillage practices (e.g. use of conservation tillage instead of plow tillage) and a soil environment that reduces residue decomposition rates.

Carbon is added to the soil by green plants that have captured CO_2 from the atmosphere by photosynthesis to form C-compounds, such as cellulose and lignin. The plant C enters the SOC pool as plant ''litter'', root material, and root exudates or, if consumed by animals, as excreta. Litter-sized plant material abrades

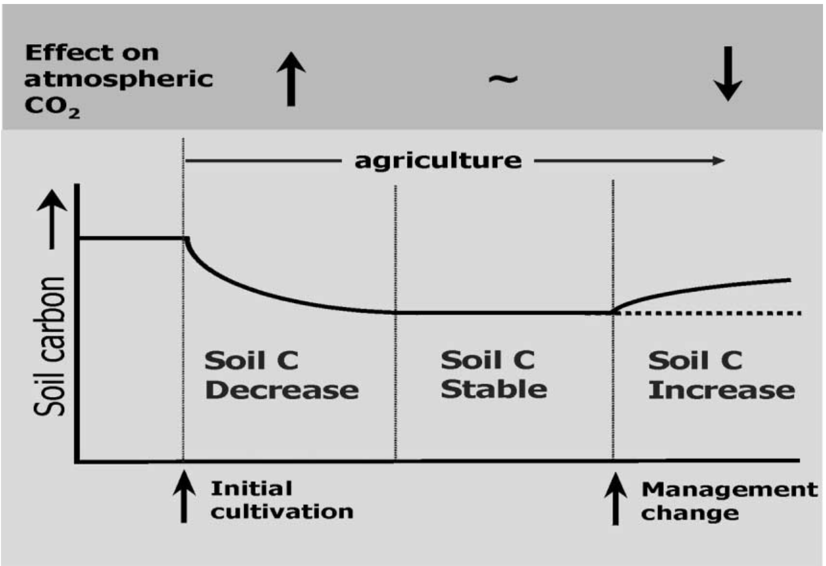

Fig. 1. Changes in the long-term storage and release of soil carbon in soil and its release as carbon dioxide as a function of agricultural practices (adapted from Janzen et al. (1998)).

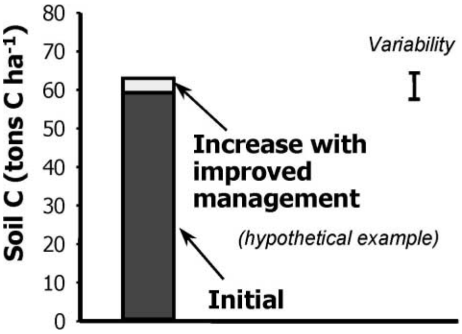

Fig. 2. The effect of improved agricultural management on the storage of carbon within a hypothetical soil profile.

into smaller sizes (i.e., 'light fraction' and/or 'particulate organic matter'). These processes are mostly near the soil surface and, therefore, the C that is accumulating is easily lost as a result of soil erosion or increased tillage intensity. Some of the C and essential elements in these fractions become a source of nutrition for soil flora and fauna, including bacteria, fungi, and micro- and macro-fauna. Microbial exudates, fungal hyphae, earthworm casts, amorphous iron and aluminum, mineral cations and anions, and complex organo-mineral compounds help form soil aggregates by binding clay mineral to particulate organic matter. Soil aggregates, complex organic-C compounds, and other pools of SOC form and breakdown continuously and their rates of breakdown and loss are sensitive to man's influence. The SOC is a food source for most soil life, so, as it is utilized, the C in the SOC is emitted as CO_2 and returns to the atmosphere.

SOC fractions can be dated using ^{14}C isotopes to determine their mean residence time (MRT). The "non-hydrolyzable-SOC" (i.e., insoluble in hot, strong hydrochloric acid) fraction provides information about the size and MRT of old-resistant SOC (Paul et al., 1997). When the size and age of this fraction are large, C-sequestration in soil is also large. Physical and/or chemical protection is provided by soil aggregates. Complex organo-mineral compounds slow microbial degradation to contribute to recalcitrant SOC that remains in soil for hundreds of years.

The length of time that SOC sequestration rates continue after adoption of improved practices is uncertain. Eventually, a new steady state is approached as the losses of C from the soil start to equal the C additions to the SOC pool. As the new steady state is approached, it will tend to be maintained until management, weather patterns, or other factors cause it to change (Fig. 1). Estimates by Lal et al. (1998) are that achieving this practical limit may require at least 50 years. In Canada, there are few observations of SOC change for conservation tillage of over 20 years and those that are available indicate that C sequestration has largely stopped (Follett and McConkey, 2000). Thus, for large-area estimations, it might be assumed that most C sequestration due to changes in tillage system are starting to approach a new equilibrium in about 25–50 years. This relationship affects the estimates of the US rates of increase in SOC sequestration during long-time periods and limits the time during which US agriculture can help offset the C emissions from other sectors of the US economy. Thus agriculture provides a window of opportunity for the other sectors to develop alternative technologies whereby their rates of CO_2 emissions can be decreased.

3. Agricultural practices to sequester C

The amount of SOC present is a function of the rate of SOC decomposition and the quantity and composition of crop residues, plant roots, and other organic material returned to the soil. Crop residues and other organic materials constitute a major resource for soil surface management, energy production, and other uses. Above-ground crop residues are highly important for enhancing the SOC content as is the C contained in the below-ground root biomass and the total biomass produced by weeds. The increase in SOC content through the return of the C in crop residues and roots to the soil depends on the quantity and quality of the residue, its management, and soil properties. Within a cropping/farming system, the equilibrium level of SOC can be related linearly to amount of crop residue applied to the soil (Larson et al., 1972; Rasmussen et al., 1980). Paustian et al. (1992) identified that higher residue lignin content also positively affects SOC accumulation. Gregorich et al. (1996) and Hassink and Whitmore (1997) observed that net rate of accumulation of SOC depends on the extent to which the soil is already filled by SOC (i.e., the size and capacity of the reservoir). Surface applied residues generally decompose more slowly than those that are incorporated by tillage because they have less contact with soil microorganisms (Reicosky et al., 1995) and soil water (Grant, 1997). Further, observations by Reicosky et al. (1997) strongly indicate that mechanical disturbance of soil by tillage increases the decomposition of SOC.

It is important to remember that the purpose of US agriculture and crop production is to produce food and other agricultural products. Agricultural practices need to be environmentally friendly. However, fertilizer use itself and the requirements for input energy to power farm machinery, pump water for irrigation, manufacture fertilizers and pesticides, and transport farm products to market also result in emissions of GHGs into the atmosphere (Table 1). Still, a major co-benefit of the use of RMPs in agriculture is that they sequester SOC. It needs to be recognized that this sequestration is a contribution by farming to the mitigation of global warming and that, with the use of scientific agriculture, the net beneficial effects are much larger than the negative effects.

4. Carbon sequestering practices on cropland

As reported by Lal et al. (1998, 1999), Bruce et al. (1999), and other authors, practices which increase residue and/or plant growth result in enhanced SOC sequestration. Use of conservation tillage (i.e., no-till, ridge-till, and mulch-tillage), maintaining higher levels of residue cover on conventionally tilled cropland, planting cropland to permanent cover such as for the CRP, and improved fertility management can increase SOC sequestration (Lal et al., 1998, 1999). Conversely, practices such as fallow, plow tillage, and abusive grazing practices that cause removal of excessive amounts of residues or vegetation for livestock can result in losses of SOC. Such losses can be by soil erosion and SOC oxidation.

5. Tillage management/cropping systems

5.1. Crop residues

Allmaras et al. (1999) estimated that as a result of the adoption of conservation tillage and the production of greatly increased amounts of residues, US cropland changed from a C source to a C sink sometime around 1984. The moldboard system was dominant for primary tillage during the 1960–1970 time frame, but Allmaras et al. (1999) estimated that only about 7% of wheat, corn, soybean, and sorghum were planted after moldboard tillage in 1993. The importance of both increased crop yields and the accompanying increases in crop residue yields must be recognized for their providing the current and future potential of US cropland soils to sequester SOC. Table 2 shows the increases in yields of both grain and residue that occurred between 1940 and 1990. Percentage increases in grain yields have been greater than the increases in crop residue yields. Sorghum grain and crop residue yields have shown the largest percent increase followed by those of corn. With the shift away from long-straw varieties, wheat shows a large grain yield increase (131%), but a small change in crop residue yields (10%). The ratios of the percent increases in grain yields to the percent increases in residue yields range from about 1.8 for soybeans to

Table 2
Grain yield, crop residue yield, and percent change in each for six selected crops, 1940 and 1990 when averaged for the United States (adapted from Allmaras et al. (1998))

Crop	Grain yield			Crop residue yield		
	1940 (kg ha^{-1})	1990 (kg ha^{-1})	Change (%)	1940 (kg ha^{-1})	1990 (kg ha^{-1})	Change (%)
Barley	1280	2920	128.1	3460	4380	26.5
Corn	1890	7310	286.8	3510	7310	108.3
Oat	1150	2010	74.8	3850	4270	10.9
Sorghum	930	3790	307.5	1800	3790	110.5
Soybean	1260	2290	81.7	2940	4250	44.6
Wheat	1050	2430	131.1	2700	2970	10.0

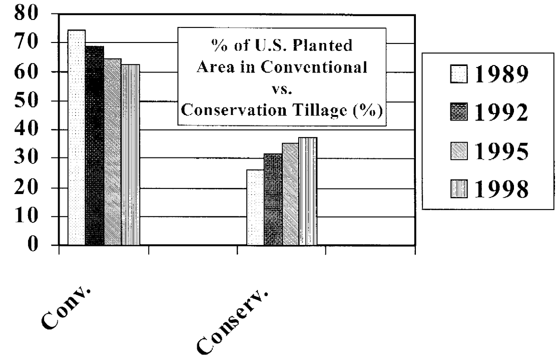

Fig. 3. Land area in conservation and conventional-tillage in the United States (1989–1998).

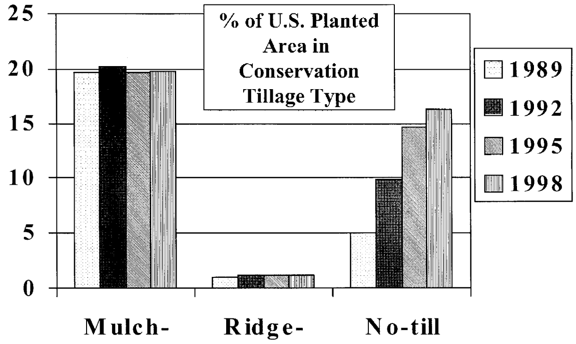

Fig. 4. Planted areas in various conservation tillage systems in the United States (1989–1998).

13.1 for wheat on a per hectare basis and average 5.2 during the period from 1940 to 1990 for the crops shown in Table 2.

5.2. Conservation tillage

Within the United States, the planted cropland area was about 113 Mha in 1989 and about 118 Mha in 1998 (CTIC, 1999). The fraction of these areas under conventional-tillage decreased from 74% in 1989 to 63% in 1998, whereas the planted area under conservation tillage increased from 26% in 1989 to 37% in 1998 (Fig. 3). These gains in the adoption of conservation tillage during this 9-year period are encouraging because of their important contributions to soil and water conservation as well as for their potential to sequester SOC. However, the fraction of the planted cropland area under conservation tillage in 1999 did not increase above that in 1998 and the overall rate of increase has been slowing (CTIC, 1999). A recent CTIC news release expresses concern that countries such as Canada, Argentina, and Brazil are aggressively encouraging increased use of conservation tillage, particularly no-till, thus decreasing their fuel and other input costs and allowing their production to become more competitive with that of the US.

Fig. 4 shows the changes in the areas in mulch-tillage, ridge-till, and no-till in the US from 1989 to 1998 (CTIC, 1999). During these 9 years, mulch-tillage increased from 22.2 to 23.4 Mha, ridge-tillage from 1.1 to 1.4 Mha, and no-till from 5.7 to 19.3 Mha. Information reported by Lal et al. (1998) indicates that, within the top 20 cm of the soil profile, the above conservation tillage practices potentially sequester C at rates of 500 kg C ha^{-1} yr^{-1} for no-till and mulch-tillage systems and 600 kg C ha^{-1} yr^{-1} for ridge-tillage systems in the US. Robertson et al. (2000) measured rates of 300 kg C ha^{-1} yr^{-1} under no-till in Michigan (USA) to a 7.5 cm depth. West and Marland (2001), using a preliminary analysis of US Department of Energy (DOE) data, indicated that conversion from conventional- to no-tillage in the US will result in sequestration of about 300 kg C ha^{-1} yr^{-1}. Follett and McConkey (2000) estimated that the sequestration rates for no-till, mulch-tillage, and ridge-tillage practices range from 300 to 600 kg C ha^{-1} yr^{-1} in the US Great Plains. McConkey et al. (1999) estimated rates of gain for conversion from conventionally tilled to no-till as 100–500 kg C ha^{-1} yr^{-1} for prairie conditions in Canada and the rates of gain for conversion from conventional-tillage to minimum tillage as 100–300 kg C ha^{-1} yr^{-1}. Gain rates are likely lower in Canada than equivalent areas of the US because soils in Canada have generally lost less of their SOC than their US counterparts since: (1) on average, they have been broken from native grass more recently, (2) arguably, have suffered less wind and water erosion, and (3) the US has higher C inputs from residue because of the higher proportion of water efficient cropping systems used in the Great Plains in the US (e.g. winter wheat, sorghum, sunflower, and corn in the US versus spring wheat and barley in Canada) (Follett and McConkey, 2000). In fact, SOC estimates using the CENTURY computer model indicate that land in the Canadian prairie provinces not under no- or minimum-till (minimum-till

= most residue on surface) is still losing SOC at rates of 0–200 kg C ha^{-1} yr^{-1} (Smith et al., 1997). Janzen et al. (1998) claim that the loss in native SOC on the Canadian prairies is largely abated at present.

The amount of SOC sequestered can be estimated by Eq. (1).

$$\text{SOC sequestered (MMTC yr}^{-1}\text{)} = \text{Land area (Mha)} \times \text{rate (kg C ha}^{-1}\text{ yr}^{-1}\text{)} \times 0.001 \quad (1)$$

In 1989, planted area of US cropland under conservation tillage was 29.0 Mha. If the rate of C sequestration for conservation tillage systems range from 300 to 600 kg C ha^{-1} yr^{-1} (Follett and McConkey, 2000) and these values are used in Eq. (1), then conservation tillage systems sequestered between 8.7 and 17.4 MMTC yr^{-1}. By 1998, the area of US cropland under conservation tillage had increased to 44.2 Mha and potentially sequestered between 13.3 and 26.5 MMTC yr^{-1}. Area of US cropland under conservation tillage for these 9 years has increased at an average rate of 1.7 Mha yr^{-1} and, based on Eq. (1), has resulted in an annual increased amount of SOC sequestered from 1989 to 1998 of 0.5–1.0 MMTC yr^{-1}. The CTIC (1999) suggests a goal of having one-half of the US cropland in the US (59.9 Mha) in conservation tillage by 2002. If such a goal was obtained, the amount of SOC sequestered would be 17.8–35.7 (Table 3). This estimate is somewhat lower, but very similar to the estimate of 24–40 MMTC yr^{-1} made by Lal et al. (1998). In addition, a goal of achieving 50% of the US cropland being planted under conservation tillage by 2002 appears overly optimistic. If the cropland area remains at the 1998 level of about 119 Mha and the annual conversion of planted area to conservation tillage continues to increase at an average annual rate of 1.7 Mha yr^{-1}, as it did between 1989 and 1998, then about 9 more years will be needed for the US to achieve having 50% of its cropland area planted to conservation tillage, an increase of another 15.3 Mha.

Table 3
Selected carbon sequestering practices in the United States

Scenario	MMTC yr^{-1}	
Tillage management/cropping systems		30.2–105.4
Conservation tillage	17.8–35.7	
Crop residue/biomass management	11–67	
Fallow reduction	1.4–2.7	
Increasing land cover		13.9–28.6
Rotations and winter cover crops	5.1–15.3	
CRP	8.8–13.3	
Production inputs (nutrients and water)[a]		10.6–30.2
Fertilizer management	6–18	
Livestock manure	3.6–9.0	
Supplemental irrigation	1.0–3.2	
Total (range)[b]		54.7–164.2
Average		109.4

[a] 1997 fertilizer-N use results in direct N_2O emissions estimated as 18.6 MMTCE of greenhouse warming potential. Neither the direct N_2O emissions resulting from N-fertilizer application nor from livestock-manures applications were calculated, but their importance is discussed by IPCC (1996) and Mosier et al. (1998). Emissions resulting from soil erosion and other energy inputs are in Table 1.

[b] These estimates of C sequestration, either do not include all the categories or estimates, are somewhat different than those made by Lal et al. (1998). For example, C-sequestration resulting from land/soil restoration is not included in the above estimate.

5.3. Crop residue and other biomass management

Besides above-ground crop residues, other important organic materials for enhancing the SOC content and C sequestration are below-ground root biomass and total biomass produced by weeds. Within a cropping/farming system, the equilibrium level of SOC can be related linearly to amount of crop residue applied to the soil (Larson et al., 1972, 1983; Rasmussen et al., 1980; Follett et al., 1987). Lal et al. (1998) estimated the amount of residue C produced on US cropland is about 447.3 MMTC, including above-ground residues and below-ground biomass plus weeds. The management of this biomass will affect the amount of SOC sequestered. It is difficult to separately estimate the effects of management as well as the C sequestration potential of individual components. However, by assuming that 50% of the residue C can be efficiently managed and then with a C-sequestration efficiency from 5 to 10%, the amount of SOC sequestered is estimated as 11.2–22.4 MMTC yr^{-1} (Eq. (1)).

Lal et al. (1998), in considering biofuels, evaluated the option of using a net amount of 112 MMTC yr^{-1} from crop residues for biofuel production. With an energy substitution factor of 0.6–0.7, C emission reduction through use of this amount of residue C as biofuel is 67–78 MMTC yr^{-1}. Thus, the potential for residue management, including biofuel, is estimated to total 11–67 MMTC yr^{-1} (Table 3). Interestingly, as part of their biofuel program, the US DOE considers corn stover as the most likely ''cost effective'' feedstock available. The DOE estimates for the use of corn stover are about 30% of the above-ground residue which could be removed for ethanol production (J. Sheehan, National Renewable Energy Laboratory, Golden, CO; personal communication, February 2000).

5.4. Fallow

Between 1964 and 1974, there was about 13.0–16.6 Mha of land in fallow. During 1987 and 1997, the area of summer fallow in the US declined from 13.0 to 8.5 Mha, or by about 35% (Smith and Young, 2000). The area of fallow in 1998 in the US was reported as 9.1 Mha (CTIC, 1999). Contrary to expectations, this decline began during a period of traditional coupled grain subsidies and low real-grain prices. The decline continued during the higher real-grain prices of 1995–1996 and the decoupled subsidies of 1996–1997. Elimination of acreage controls in the 1996 farm bill and the CRP probably help keep idled land from returning to fallow.

Land in summer fallow has likely lost much of its SOC in the past and as such would have considerable potential to sequester SOC under improved tillage and or residue management conditions. If the management of such land remained in a long-term static condition, then the soil is currently neither sequestering nor losing much additional SOC. However, other reports indicate that maintaining a fallow-based system likely results in continued degradation and loss of SOC (Rasmussen et al., 1980; Campbell et al., 1991; Angers, 1992). Lal et al. (1998) assumed that SOC sequestration rates for land removed from fallow would range between 100 and 300 kg C ha^{-1} yr^{-1} because much of the fallow area is in the dryer climates in the US Great Plains. More recently, Follett and McConkey (2000) in writing about fallow in the North American Great Plains estimated sequestration rates of 300–600 kg C ha^{-1} yr^{-1} in the US and 200–300 kg C ha^{-1} yr^{-1} in Canada. If the 8.5–9.1 Mha of US land in fallow (reported above) were placed under conservation tillage and/or permanent vegetative cover and sequestered between 300 and 600 kg C ha^{-1} yr^{-1}, then the additional SOC sequestered (Eq. (1)) would be 2.6–5.5 MMTC yr^{-1}. However, because fallow is usually reduced, but not eliminated, then a reasonable estimate for the shorter term might be to decrease the estimates by one-half. If this was done, annual SOC sequestration for fallow is 1.4–2.7 MMTC yr^{-1} (Table 3).

6. Increasing land cover

6.1. Rotation and winter cover crops

Growing crops is a major land use in the US Principle crops including small grains, such as wheat and barley, corn, sorghum, and soybeans. Increasing SOC sequestration in cropland requires the addition of enough crop residue biomass and the incorporation of its C into SOC that the annual losses of soil C from oxidation and gaseous losses, erosion, leaching or other loss mechanisms are exceeded. Strategies that increase the cropping intensity such as the use of rotations with winter cover crops to increase the amount of biomass C returned to the soil can affect the size, turnover, and vertical distribution of both active and passive pools of SOC (Franzluebbers et al., 1994). If suited to the climate and the farming operation, then such cropping systems provide an opportunity to produce more biomass C than in a monoculture system and to thus increase SOC sequestration. Lal et al. (1998) reviewed the literature on this topic and concluded that the potential exists for adopting winter cover crop rotation systems on about 51 Mha which could sequester an additional 100–300 kg C ha^{-1} yr^{-1}, thus resulting in 5.1–15.3 MMTC yr^{-1} (Table 3).

6.2. Conservative reserve program (CRP)

In October 1999, the US had 12.65 Mha of land under CRP contract (USDA, 2000). The CRP is important for sequestering SOC both because of the large areas involved and because of the high rates of SOC sequestration obtained (Gebhart et al., 1994; Lal et al., 1999; Reeder et al., 1998; Unger, 2001). These and other publications provide field measurements from throughout the Great Plains of the amounts of

SOC sequestered by CRP. In general agreement with the above studies for the rates of SOC sequestration is the one by Follett et al. (2001), whose estimates of total annual amounts of SOC sequestered by the CRP are for 5.6 Mha of land under the CRP across a 13 State region. Their estimates across this large region of the US are that the CRP sequesters 570, 740 and 910 kg SOC ha^{-1} yr^{-1} in the 0–5, 0–10 and 0–20 cm depth increments, respectively. Using values between 600 and 900 kg SOC ha^{-1} yr^{-1} for sequestration under CRP in Eq. (1), then the 12.75 Mha land currently under the CRP (USDA, 2000) in the US sequesters 7.6–11.5 MMTC yr^{-1} (Table 3). At 100% enrollment, the amount of land in the CRP would total 14.73 Mha, thus potentially sequestering an additional 1.2–1.8, for a total of 8.8–13.3 MMTC yr^{-1}.

7. Production inputs

7.1. Cultivated cropland

Practices that require lower energy inputs, such as no-till versus conventional-tillage, generally result in lower inputs of fuel and a consequent decrease of CO_2-C emissions into the atmosphere per unit of land under cultivation. If those practices that require greater power inputs can be replaced by others that require less energy, they will result in less fuel use per trip, e.g. plowing a field requires more fuel than does an application of pesticide by spraying. Whenever the number of trips across the field can be decreased, it also decreases the amount of fuel used. A recent analysis of energy use in agriculture (USDA, 1997a) identified a general decrease for most fuel types, with perhaps the exception of diesel. Diesel has become the major type of fuel used in tractors, harvesters, and often for transporting harvested crops to market. Additional options for on-farm reductions in fossil-fuel use include the increased potential to use plant-based fuels such as "soy-diesel" and "gasohol". Plant-based fuels have the advantage of recycling CO_2-C fixed by photosynthesis back into the atmosphere rather than emitting CO_2-C obtained from fossil-fuel sources.

The CO_2-C emissions from diesel used in agriculture of about 59,000 million liters (USDA, 1997b) (excluding diesel use for irrigation) is estimated as 10.8 MMTC yr^{-1}. If the entire amount was used for only field operations (tillage, planting, pest control, and harvesting), it would amount to the emission of about 82 kg CO_2-C ha^{-1} yr^{-1}. West and Marland (2001) recently estimated that CO_2-C emissions from agricultural machinery used in farm operations for conservation-, reduced-, and no-tillage practices were 72, 45 and 23 kg C ha^{-1} yr^{-1}, respectively. It is important to speak in realistic terms about the fuel use for field operations on an annual basis and to realize that on-farm efficiencies are improving. Data from the fuel use records of farmers that were interviewed indicate that those using no-till use about 45 l of diesel ha^{-1} yr^{-1} (Gerald Lynch, corn and soybean farmer, near Decatur, IL; personal communication, June 2000) to perform five field operations (from planting to harvest) and that an average of about 9 l of diesel ha^{-1} are required per field operation, whereas crops that require additional operations (such as possibly the growing of cotton or rice) may require up to about 84 l of diesel ha^{-1} yr^{-1}. Use of 27 l (three field operations) to 84 l of diesel ha^{-1} yr^{-1} is equivalent to 20–62 kg CO_2-C emissions ha^{-1} yr^{-1}. Consequently, these estimates are directly in line with those by West and Marland (2001) and indicate that CO_2-C emissions from field operation for cultivated acres in the US range between 2.7 and 8.1 MMTC yr^{-1}.

7.2. Fertilizer management

Soil fertility status affects biomass production, which in turn can directly affect the quantity of crop residues returned to the soil and thus SOC sequestration. Lal et al. (1998) summarized the results of a number of studies and concluded that fertility management practices can enhance the SOC content at the rate of 50–150 kg ha^{-1} yr^{-1}. In a dryland annual cropping study after 11 crops in CO, Halvorson et al. (1999) observed that fertilizer N rates of 67 and 134 kg N ha^{-1} yr^{-1} resulted in 140 and 182 kg ha^{-1} yr^{-1} more SOC, respectively, in the 0–15 cm depth than for the zero N treatment. In a further analysis, Halvorson et al. (2000) considered three additional long-term cropping systems studies in the US as follows: a dryland wheat–corn (sorghum)–fallow rotation in Colorado, a dryland cropping systems study in North Dakota, and an irrigated sugarbeet–small-grain rotation study in Montana. He concluded that managing N fertilization for optimum yield significantly increased crop residue inputs at all locations which in most cases resulted in increased SOC levels. Carbon sequestration efficiency was improved by N fertilization and contributed to improving soil quality at all sites.

The US uses about 11.5 MMT fertilizer N yr^{-1}, enough that if applied uniformly on the 119 Mha of US cropland which would average 97 kg N ha^{-1} yr^{-1}. Besides fertilizer N, phosphorus, potassium, and often secondary and trace mineral nutrients are also used. It can generally be assumed that adequate amounts of nutrients can be made available for use on US croplands. Thus, for the 119 Mha of planted US ropland area, the amount of SOC sequestered (Eq. (1)) is between 6 and 18 MMTC yr^{-1} as a result of fertilizer management (Table 3) and may be much higher if the rates of SOC sequestration resulting from fertilization are indeed larger as suggested by Lal et al. (1998).

The purpose for the use of N-fertilizer is to increase crop yields and improve the economic return realized by the producer, with the sequestration of C as a secondary benefit. However, the benefit for offsetting GWP from increased soil C sequestration that results from N fertilization may be largely negated by the combined effects of the amounts of CO_2-C emitted during the manufacture of N-fertilizers and from the nitrous oxide (N_2O) produced during nitrification and especially during denitrification of the applied fertilizer N.

Based upon data reported by Lal et al. (1998) and USDA (1997a), N-fertilizer manufacture results in about 0.82 kg CO_2-C emission per kg N produced. West and Marland (2001) report that CO_2-C emissions for the production of fertilizers are 0.81, 1.10 and 0.08 kg CO_2-C per kg N, P_2O_5, and K_2O, respectively. Izaurralde et al. (1997) reported a value of 1.23 kg CO_2-C per kg N that included post-production CO_2-C emissions resulting from storage, transportation, and application that. Post-production emissions by West and Marland (2001) are reported as 0.04, 0.06 and 0.05 kg CO_2-C per kg N, P_2O_5, and K_2O, respectively, and include mineral transportation to the production facility, then to the supply center, and finally to the application site. Not included are CO_2-C emissions for application on the field since fertilization is crop, field and nutrient specific, whether a nutrient is applied annually or not, and the likelihood of its application as part of another field operation.

Nitrous oxide is a GHG that has a GWP of 310 (during 100 years relative to CO_2). Anthropogenic N inputs into agricultural systems include N from synthetic fertilizer, animal wastes, increased biological N-fixation, crop residue returned to the field, cultivation of organic soils and enhanced organic matter mineralization. Ammonia and oxides of N (NO_x) can be emitted from agricultural systems and, along with other forms of N, may be transported off-site and serve to fertilize other systems. Nitrous oxide may be emitted directly to the atmosphere in agricultural fields, animal confinements or from pastoral systems. Mosier et al. (1998) evaluated the IPCC methodology (IPCC, 1997) as part of an effort to provide a more comprehensive N_2O emission calculation methodology. Using mid-point values, they recommended that the emission factor relating N_2O directly from soil to fertilizer-N application should be $1.25 \pm 1\%$ N_2O-N of fertilizer N applied. If both direct and indirect emissions are considered, about 2.0% of N input into agricultural system would be emitted as N_2O-N annually. Because of the climate forcing potential of N_2O compared to CO_2, then each kg N ha^{-1} applied to an agricultural field requires an offset of about 1.66 kg carbon equivalent (CE) ha^{-1} yr^{-1} to balance the direct GWP effect and 2.65 kg CE ha^{-1} yr^{-1} to balance the direct plus the indirect GWP effect of the N_2O emissions that result. Therefore, the 11.5 MMT fertilizer N used in the United States can be estimated to result in 19 and 30 MMTCE yr^{-1} of direct and direct plus indirect N_2O emissions, respectively. However, the indirect cycling of N, as the fertilizer N cycles through the environment and increases the GWP effect above the direct effect, also can include an effect on biomass yields and potential additional off-site SOC sequestration.

7.3. Livestock manure

Nutrients from animal manure represents a valuable resource in the US and here we consider primarily the nutrients in manure from confined livestock operations. "Confined" livestock are those produced under any type of operation where manure can typically be recovered, i.e., collected, stored, and available for use as a nutrient resource. The livestock categories included here are dairy or beef cattle (*Bos taurus*), swine (*Sus scrofa domesticus*), chickens (*Gallus gallus domesticus*), and turkeys (*Meleagris gallopavo*). The above categories referred to are dairy (milk cows and heifers); beef (steers-bulls-calves and cows); hogs and pigs (growers and breeders); and poultry (broilers and layers, and turkeys) (USDA, 1995, 1996). The procedure used for calculating annual weight of manure N produced is from Lander et al. (1998). Calculations used here are only for manure in those regions of the US where it can economically be applied to cropland. Following calculation of the weight of N contained in manure from confined livestock in the US, an estimate was made that an average application rate of manure that would be equivalent to applying 250 kg N ha^{-1} yr^{-1} could be made to 18 Mha of cropland. We estimated that application of manure in the US, as described above, would result in sequestration at the rate of 200–500 kg C ha^{-1} yr^{-1}, thus resulting in a potential total sequestration of 3.6–9.0 MMTC yr^{-1} (Table 3).

7.4. Irrigation

Irrigated land area in the US is about 20.2 Mha (USDA, 1997b). Water application is important for increasing biomass yields. Lal et al. (1998) estimated that irrigation results in a SOC sequestration rate of between 50 and 150 kg ha^{-1} yr^{-1}. Using SOC sequestration rates of 50–150 kg SOC ha^{-1} yr^{-1} in Eq. (1), then 20 Mha of irrigated cropland sequesters between 1.0 and 3.0 MMTC yr^{-1} (Table 3). Research data on SOC sequestration under irrigation is scarce and more information is greatly needed. The estimates by Lal et al. (1998) are likely too conservative. In addition, the potential of irrigated agriculture to sequester C can be increased considerably by applying improved technology. Irrigated fields often undergo more intensive tillage than is required and crop residues are often harvested instead of being returned to the soil. Cropping sequences that produce only crops with residues that have a low C:N ratio can result in more rapid decomposition than for residues with high C:N ratios. Also serious can be enhanced potential for soil erosion and the associated degradation and loss of SOC caused by erosion (see Footnote c, Table 1).

The area of irrigated land in the US is about 20.2 Mha with about 15.5 Mha irrigated by pumping (USDA, 1997b) and the remainder is irrigated by gravity. Gravity irrigation is the delivery of water to the field through a ditch and then the use of gravity flow of the water down furrows (USDA, 1997b). Gravity irrigated land does not require the use of energy for pumping and thus there are no associated CO_2 emissions. Hydro-electric and nuclear-electric powered pumps also do not result in CO_2 emissions. For this discussion, it was estimated that the electricity used to pump irrigation water in the US is derived from a combination of coal (45%), hydro-electric (40%), and nuclear (15%) powered generation sources (Table 4). The energy sources used for the 15.5 Mha of pump irrigated land in the US are electricity (52.6%), diesel (26.8%), natural gas (15.9%), propane (4.3%), and gasoline (0.4%). Pumping irrigation water

Table 4
Energy sources, area, and C emissions for irrigated cropland in the United States

Energy source	Area irrigated[a]			CO_2-C
	By pumping (ha)	Energy use (Quads yr^{-1})	C-emission (MMTC yr^{-1})	Emission (kg C ha^{-1} yr^{-1})
Electricity[b]	8157210	0.1216	1.39	171
Natural gas	2463418	0.0406	0.59	239
Propane	660139	0.0032	0.06	85
Diesel	4160861	0.0491	0.98	236
Gasoline	64356	0.0011	0.02	334
Pumping (total)	15505994		3.04	196
All irrigated (total)	20246509			150

[a] USDA, 1997b.

[b] Electricity for irrigation in the US was estimated to be generated by 45% from coal, 40% from hydro-electric, and 15% from nuclear power.

results in the emission of about 3.0 MMTC yr^{-1}. The CO_2-C associated emissions from pumping water to irrigate land (15.5 Mha) is about 200 kg C ha^{-1} yr^{-1} (range 85–330 kg C ha^{-1} yr^{-1}) and depends upon the source of energy used. If the CO_2-C emissions resulting from pumping irrigation water are weighted across the total 20.2 Mha of irrigated land (Table 4), then they average about 150 kg C ha^{-1} yr^{-1}. Comparable estimates by West and Marland (2001) are that CO_2-C emissions from pumping water to irrigate 14.5 Mha are 240 kg C ha^{-1} yr^{-1} with a range 125–285 kg C ha^{-1} yr^{-1} that again depends upon the energy source. Another report of energy use for irrigation in the US (Schlesinger, 1999) is that fossil-fuel derived energy used in pumping irrigation water ranges between 22 and 83 g C m^{-2} yr^{-1} (220–830 kg C ha^{-1} yr^{-1}), but it is difficult to evaluate the basis for these data. Improvements in water use efficiency (crop biomass/unit of water), equipment efficiencies, and other improved technologies are expected to continue to help to decrease C emissions resulting from irrigation in the US. Such technologies include irrigation scheduling and precipitation accounting to decrease irrigation water use, more efficient irrigation systems and power generation, and improved crop varieties and nutrient use.

8. Research needs

Although a broad base of knowledge is developing about the general and qualitative effects of soil management on SOC sequestration, quantitative estimates of rates of SOC sequestration for various cropping systems and geographic regions need to be greatly improved. Information is needed about the properties of various storage forms of sequestered SOC. What are the storage processes and rates of formation for various SOC pools? For example, a process that correlated with the mean weight diameter of water stable aggregates is their C content under alfalfa, but not under corn or fallow (Angers, 1992). Much more needs to be known about the rates of aggregate formation; their stability and longevity; the relationships of their formation to tillage practices, soil characteristics, and residue quality; and if and how various effective soil management practices are in relation to the MRT of soil aggregates and aggregate sizes, thus perhaps extending the amount of time that SOC remains sequestered. Understanding must be developed about the rates of accumulation and rates of degradation of SOC pools, which pools and chemical forms are most recalcitrant, and what processes are involved in the physical protection of SOC. Long-term studies, including those using the measurement of C isotopes in various SOC fractions, have the potential to provide a basic understanding of some of the processes involved in both degradation and aggradation of SOC. Follett et al. (1997) observed that for small-grain–fallow rotation systems, the efficiency of incorporation of crop residue C was about 5.4% at Akron, Colorado (US) during 84 years and about 10.5% at Sidney, Nebraska (US) during 20 years. Such information is needed for other crops, cropping systems, crop residues, and tillage managements.

Maintenance of or even restoration of SOM levels may help provide a long-term measure of the effectiveness of conservation practices in maintaining soil productivity (Follett et al., 1987) and possibly increasing the net income to producers. The SOM in soil is normally considered to contain about 58% SOC. Bauer and Black (1994) estimated that 1 MT of SOM ha^{-1} resulted in an increase in soil productivity equal to 35.2 kg ha^{-1} for spring wheat total aerial dry matter and 15.6 kg ha^{-1} for grain yield in the northern Great Plains. For 134 fields in the semiarid Argentine pampas, Diaz-Zorita et al. (1999) observed that wheat yields were related to both soil water retention and total SOC. In their study, the loss of 1 MT of SOM ha^{-1} was associated with a decrease in grain yield of about 40 kg ha^{-1}. The function of SOC in relation to soil productivity needs to be understood. To what degree does SOC relate to the fertility of the soil and to what degree does it relate to other important factors such as water holding capacity.

It is important to understand the relation of depletion of SOM to the concomitant loss of soil fertility and thus to loss of soil productivity (Bauer and Black, 1994). Losses of soil fertility in the form of decreased SOC and especially loss of topsoil depth can seriously decrease crop yields. In Missouri, Kitchen et al. (1999) observed corn yields ranging from 2500–3800 kg ha^{-1} with 15 cm of topsoil to 8800–10,000 kg ha^{-1} with 60–90 cm of topsoil. Unger and Baumhardt (1999) studied factors related to dryland grain sorghum yield increases in the southern Great Plains from

1939 to 1997 and concluded that of the 139% increase in yields that had occurred, 46% was the result of improved hybrids, but the other 93% was the result of other factors and mainly soil water content at planting resulting from the adoption of improved crop residue management. However, the authors did not determine the relation of crop residue management which was not related to soil fertility changes, SOC, or soil water holding capacities, which may or may not have been the factors. Certainly, there is little question that for the southern Great Plains, water storage efficiency for the periods between crops is critical and with no-tillage, water storage efficiencies of 35–50% have been obtained compared to 15–30% with sweep and disk tillage (Unger, 1999).

Information is increasing concerning the amounts of SOC sequestered as a result of improved nutrient management, especially N. However, the evidence that N fertilizers contributes heavily to emissions of N_2O begs for improved management practices that result in higher N-use efficiencies to decrease this effect. More information is needed about the effectiveness of using livestock manures and of biological N fixation for SOC sequestration and potential rates of N_2O emission as a result of these sources per unit of SOC sequestered. In addition, there is insufficient information about amounts of SOC sequestered as a result of the use of other plant nutrients such as phosphorus, potassium, or secondary and minor nutrients.

Information is needed about the degree to which above-ground- versus below-ground-residue resources, including the effects of crop type, contribute to the amount of SOC sequestered in response to soil management practices. More information at the local and State level is needed about rates of SOC sequestration that results from use of the CRP, soil types, and species of vegetation planted. This same type of information is needed for various types of crop rotations and winter cover crops. Much more needs to be known about SOC sequestration under irrigated agricultural systems. Especially important is the development of more effective management systems for the use of crop residues and a decrease in the amounts of soil erosion (water and wind) that occur from irrigated cropland. Such decreases especially require a reduction in the amount of tillage used on irrigated land and the development of methods and equipment whereby conservation tillage can be effectively utilized under various irrigation systems.

9. Additional considerations

In the future, US agriculture faces the continuing challenge to increase production per unit of land in order to be economically viable and globally competitive. Additionally, agriculture must reduce even more its ecological footprints in the form of soil erosion-sediment discharges, nutrient and pesticide leakages, and organic matter-soil carbon losses (Miller, 1999). Maintenance of and restoration of SOM levels are long-term measures of the effectiveness of conservation practices in preserving soil productivity (Follett et al., 1987). Conservation tillage is receiving much focus as an alternative to the use of conventional-tillage systems and as a means to sequester SOC. Conservation tillage can work under many situations and is cost effective from a labor stand point. This is illustrated by data collected from a subsample of corn producers which indicates that owner-operators and share-renters had similar adoption rates of conservation tillage and that cash-renters had the lowest adoption rate (Fig. 5). However, cash-renters and share-renters were much less likely to adopt long-term conservation practices such as contour farming, strip cropping, and grassed waterways than were the owner-operators. This study indicates that land tenure likely has major implications for the way that land resources are managed and for environmental quality. Such implications also hold challenges for the design and implementation of future agricultural programs and policies. At least in some parts of the US, conservation tillage is being noted as, "losing out to tillage... because of changes in policy, and yield advantages among other things" (D.R. Keeney, Leopold Center for Sustainable Agriculture, Ames, IA, personal communication; September 1999). Keeney goes on to state, "I have been getting the impression that agricultural's role in climate change mitigation is gradually being reduced to the use of conservation tillage." The statements of Keeney coupled with the concerns expressed by the CTIC (1999) that rates of adoption of conservation tillage are slowing and that adoption in 1999 did not increase above that in 1998 must give concern to scientists conducting tillage research as well as to many others.

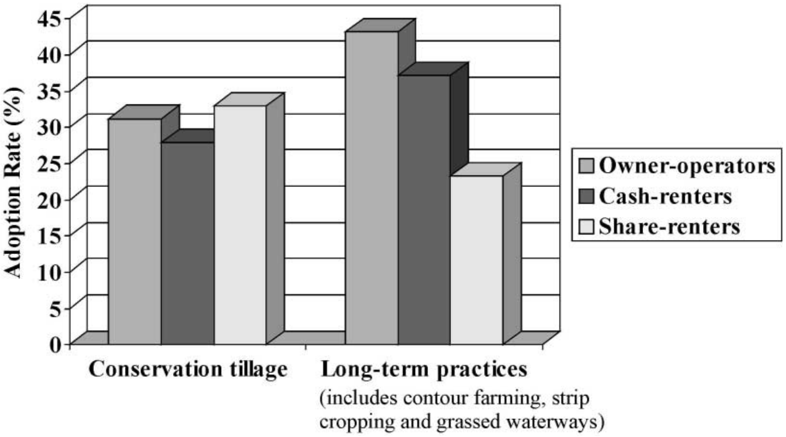

Fig. 5. Land tenure relations to the adoption of conservation tillage and long-term conservation practices (USDA, 1996).

The estimates made by Lal et al. (1998), by other authors, and those in this paper all point to the fact that US agriculture can make a major contribution to sequestering atmospheric CO_2 as SOC. Conservation tillage systems have great potential to sequester SOC. However, the factors and risks that concern farmers and affect their adoption of conservation tillage, especially its adoption by various land tenure groups, must be considered. Research on the potential of agricultural soils to help mitigate the greenhouse effect is a rapidly developing area of technology. However, of necessity, the understanding of this technology is overlaid on top of a long list of issues that a successful US agricultural industry must continue to address. The land tenure issue is mentioned above and is an intrinsic component for US agriculture's being a successful economic enterprise.

Additional societal concerns will continue about the control of losses of sediments and chemical from agricultural lands, water quality, odors, and airborne particulate matter, as well as GHG emissions. All these important topics are part of the public forums of today and farmers and farming practices will continue to be under scrutiny because of them.

Recognizing that many challenges exist for US agriculture, there are many positive factors that relate to agriculture's role in sequestering C to help mitigate the greenhouse effect. Most importantly is the practices that sequester SOC contribute to environmental quality and the development of a sustainable agriculture. Tillage or other practices that destroy SOM or cause its loss and result in a net decrease in SOC do not result in a sustainable agriculture. Sustainable agricultural systems involve those cultural practices that increase productivity while enhancing C sequestration in soil. Crop residue management, conservation tillage, efficient management of nutrients, precision farming, efficient management of water, and restoration of degraded soils. These are the win–win strategies for a sustainable agriculture. Importantly, the practices that achieve SOC sequestration are consistent with good land stewardship and result in SOC sequestration being a win–win situation.

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