6

Management of Dryland Cropping Systems in the U.S. Great Plains: Effects on Soil Organic Carbon

Mark A. Liebig
USDA-ARS, Northern Great Plains Research Laboratory, Mandan, ND

M.M. Mikha
USDA-ARS, Central Great Plains Research Station, Akron, CO

Kenneth N. Potter
USDA-ARS, Temple, TX

The expansion and intensification of agroecosystems worldwide has significantly affected the environment at multiple spatial scales (Matson et al., 1997). Agroecosystem effects on atmospheric constituents have altered local, regional, and global environmental quality through windblown soil (Zhang et al., 2001) and emission of particulate matter, reactive N (e.g., NH_3 and NO_x), volatile organic compounds, hydrogen sulfide, and greenhouse gases (GHGs) (Aneja et al., 2006; Franzluebbers and Follett, 2005). The contribution of agroecosystems to GHG emission, in particular, has received increased international attention given the role of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) to increase radiative forcing of the Earth's atmosphere (IPCC, 2007), which is the underlying cause of global climate change (Oreskes, 2004; Brown, 2006). Projected changes in climate from elevated concentrations of GHGs in the Earth's atmosphere include increased mean global temperatures of 1.5 to 4.5°C (Mahlman, 1997), shifts in vegetation zones toward the poles (or disappearance entirely, due to sea level rise), and a more vigorous hydrological cycle (Rosenzweig and Hillel, 1998). Such projections do not portend well for agriculture and will require the development of resilient agroecosystems to meet future demand for food, feed, and fiber.

Mitigation of GHG emission from agroecosystems requires increasing soil organic carbon (SOC), decreasing CH_4 and N_2O emissions, or increasing soil CH_4 oxidation (Robertson et al., 2000; Mosier et al., 2003). To date, much emphasis

Soil Carbon Sequestration and the Greenhouse Effect, 2nd edition. SSSA Special Publication 57.

has been placed on identifying and employing land management practices that sequester SOC (Lal et al., 1999; Lal, 2004). While increasing SOC in agricultural lands is finite in capacity and time, it does provide an important bridge to reduce CO_2 emissions from agroecosystems until new technologies to reduce global dependence on fossil fuels are developed and employed.

The objective of this chapter is to provide a synopsis of management effects on SOC dynamics within dryland cropping systems of the U.S. Great Plains. This region possesses significant expanses of land used for agricultural production. Accordingly, identification and application of dryland cropping systems that sequester SOC can have a significant impact on the overall GHG balance from U.S. agriculture.

Climate, Soils, and Land Use

The U.S. Great Plains extends from Canada to Mexico within the middle quarter of the contiguous United States (Fig. 6–1). The region occupies approximately 150 Mha and is delineated by Land Resource Regions F (Northern Great Plains Spring Wheat Region), G (Western Great Plains Range and Irrigation Region), and H (Central Great Plains Winter Wheat and Range Region) (Soil Survey Staff, 1981). States within the region include parts of Montana, North Dakota, South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma, and Texas.

Climate within the U.S. Great Plains is classified as semiarid to subhumid continental, with evaporation exceeding precipitation in most years (Bailey, 1995). Typically, winters are cold and dry, and summers warm to hot with erratic precipitation. Annual precipitation ranges from 250 to 750 mm and increases from west to east. Annual temperature ranges from 4°C in the northwest to 18°C in

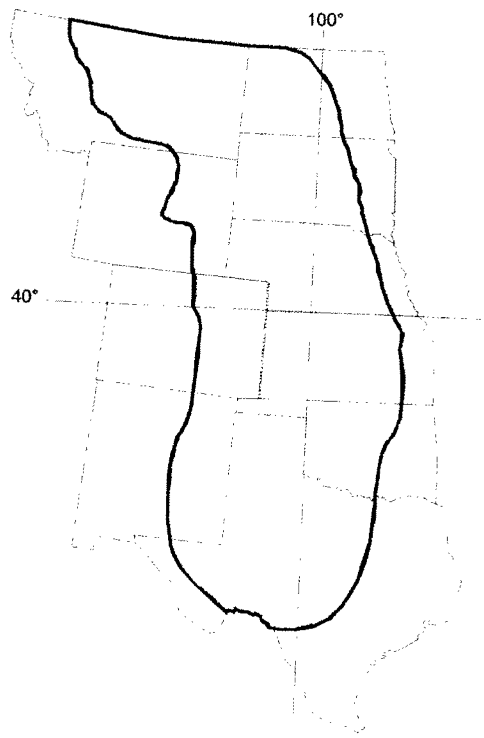

Fig. 6–1. Approximate boundaries of U.S. Great Plains. (Adapted from Aandahl, 1972, and Bailey, 1995.)

the southeast. Accordingly, the average number of frost-free days is lowest in the north (100 d) and greatest in the south (240 d) (Bailey, 1995). While averages for climatic variables provide a general understanding of environmental conditions for agricultural production, the region's defining climatic characteristic is its variability, as droughts, wet periods, intense precipitation events, and extreme temperatures are common (Peterson et al., 1996).

Organic matter accumulation and calcification are the primary pedogenic processes in the U.S. Great Plains. Soil organic matter tends to increase in surface depths with increasing precipitation, while large amounts of precipitated calcium are present at lower depths. Taxonomically, Mollisols are prevalent throughout the region, with Ustolls as the dominant suborder. Other soil orders found in the region (by decreasing prevalence) include Entisols, Aridisols, Alfisols, Inceptisols, and Vertisols (Soil Survey Staff, 1999).

Agriculture is the prevalent land use throughout the region, with rangeland and cropland occupying over 90% of the total land area (U.S. Census Bureau, 2007). Area of cropland occupies approximately 45 Mha, with >75% under dryland (nonirrigated) conditions (National Agricultural Statistics Service, 2007). Crop distribution under dryland conditions varies considerably in the region. In the northern part of the region, cereal crops such as hard red spring wheat (*Triticum aestivum* L.), winter wheat, and barley (*Hordeum vulgare* L.) are predominant, but a significant emphasis on crop diversification since the 1980s has expanded crop portfolios to include oilseed, pulse, and forage crops (Padbury et al., 2002). Spring and winter wheat are primary crops in the central and southern portion of the region, with corn (*Zea mays* L.), sorghum [*Sorghum bicolor* (L.) Moench], proso millet (*Panicum miliaceum* L.), cotton (*Gossypium* spp.), and sunflower (*Helianthus annuus* L.) comprising the majority of alternative crops (Westfall et al., 1996). Fallow periods are common throughout the region due to absence of consistent precipitation and may occupy up to 35% of cropland area in any given year (Padbury, 2003). However, advances in weed and residue management technology have contributed to a decreasing trend in the frequency of fallow throughout the region (Tanaka et al., 2007).

Historical Effects of Dryland Cropping Systems on Soil Organic Carbon

Conversion of native vegetation to dryland cropping in the U.S. Great Plains has resulted in a significant decrease in SOC. Historical studies across multiple locations in the region indicate a relative SOC loss of 42 ± 11% (7.7 ± 5.2 g C kg^{-1}) for near-surface (<30.5 cm) depths (Table 6–1). Cropping practices evaluated in these studies relied heavily on the use of intensive tillage and fallow for the production of corn and a variety of small grains (Haas et al., 1957). This estimate of relative SOC loss is consistent with other estimates for the region, which range from 23 to 53% (Donigian et al., 1994; Cihacek and Ulmer, 1995). When scaled to cropland area in the region, the absolute SOC change from conversion of native vegetation to cropping reflects a loss of 1100 Tg C; approximately one-fifth of the total SOC estimated to have been lost in the United States as a result of land use change to crop production agriculture (Lal et al., 1999).

Given the known effect of climate on SOC dynamics (Burke et al., 1989), data from historical studies were partitioned by subregion. Initial SOC values under

Table 6–1. Soil organic carbon (SOC) loss following conversion to cropping in the U.S. Great Plains.

Location	Textural class†	Soil horizon depth	Years under cultivation	SOC loss		Reference‡
		cm		Relative %	g C kg^{-1} soil	
Mandan, ND	SL	0–15.2	30	31	6.6	1
Dickinson, ND	L	0–15.2	40	59	21.3	1
Havre, MT	CL	0–15.2	31	53	9.2	1
Moccasin, MT	CL	0–15.2	39	32	10.5	1
Sheridan, WY	L	0–15.2	30	28	4.7	1
Archer, WY	L	0–15.2	34	41	5.5	1
Akron, CO	SiL	0–15.2	39	46	6.5	1
Colby, KS	SiL	0–15.2	41	45	8.2	1
Hays, KS	SiCL	0–15.2	43	51	12.6	1
Garden City, KS	SL	0–15.2	39	39	4.4	1
Dalhart, TX	L	0–15.2	39	39	2.8	1
Nebraska	Variable	0–30.5	45–60	28	NR§	2
Hays, KS	SiCL	0–17.5	40	25	4.5	3
North central KS	SiL/SiCL	0–17.8	>30	51	6.5	4
South central KS	SiL/SiCL	0–17.8	>30	26	4.1	4
Northeast CO	SL	0–15	60	62	6.3	5
TX Panhandle	SL	0–30	75	32	2.4	6
Temple, TX	C	0–20	120	47	15.2	7

† C, clay; CL, clay loam; L, loam; SiL, silt loam; SiCL, silty clay loam; SL, sandy loam.

‡ 1, Haas et al., 1957; 2, Russel, 1929; 3, Hobbs and Brown, 1965; 4, Hide and Metzger, 1939; 5, Bowman et al., 1990; 6, Bronson et al., 2004; 7, Potter et al., 1998.

§ NR, not reported.

native vegetation were higher in the north subregion (Montana, North Dakota, northern Wyoming) than the central (southern Wyoming, Colorado, Nebraska, Kansas) and south (Oklahoma, New Mexico, Texas) subregions, indicating a strong climatic effect on SOC content (Fig. 6–2). Relative SOC losses from conversion to cropping across subregions, however, were relatively constant (39 to 43%), resulting in greater absolute SOC losses from cropland in the north (10.5 g C kg^{-1}) relative to the central (6.5 g C kg^{-1}) and south (6.8 g C kg^{-1}) subregions. Assuming SOC under native vegetation represents maximal accretion values for dryland conditions, these historical data suggest a greater capacity to store more SOC with improved management in northern latitudes of the U.S. Great Plains.

Reversing Soil Organic Carbon Decline through Management

Management factors that affect SOC do so by influencing C input from plant litter and C loss via soil respiration, the rates of which determine the overall steady state for SOC (Janzen et al., 1998). Within dryland cropping systems in the Great Plains, management factors often have subtle effects on SOC on an annual time scale (Mikha et al., 2006), and it can take years or even decades before an effect of management on SOC is discernable. Consequently, long-term research sites are

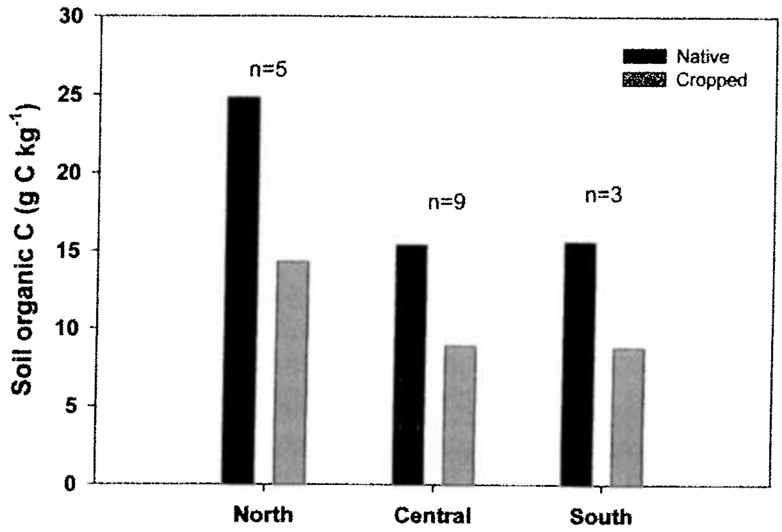

Fig. 6–2. Historical changes in soil organic carbon from conversion to cropping within subregions of the U.S. Great Plains.

essential for estimating management impacts on SOC (Richter et al., 2007). Unfortunately, there are few long-term dryland cropping system experiments in the U.S. Great Plains where SOC assessments have been part of ongoing data collection efforts (Table 6–2). Furthermore, management factors affecting SOC change within these experiments have largely been limited to three general categories: tillage, cropping intensity, and application of crop nutrients.

Table 6–2. A partial list of long-term dryland cropping experiments established since 1960 in the U.S. Great Plains.

Study location	Treatments	Year initiated	Reference†
Culbertson, MT	Cropping intensity, tillage	1983	1
Mandan, ND	Cropping intensity, tillage, N fertilization	1984‡	2
Mandan, ND	Cropping intensity, tillage	1993	3
Sidney, NE	Tillage, N fertilization	1967/1970	4
Akron, CO	Tillage	1967‡	5
Akron, CO	N fertilization	1984‡	6
Akron, CO	Cropping intensity	1990	7
Sterling, CO	Cropping intensity, landscape position (low potential evapotranspiration	1985	8
Stratton, CO	Cropping intensity, landscape position (medium potential evapotranspiration)	1985	8
Walsh, CO	Cropping intensity, landscape position (high potential evapotranspiration)	1985	8
Bushland, TX	Cropping intensity, tillage, N fertilization	1983	9
Temple, TX	Tillage, N fertilization	1981	9

† 1, Pikul and Aase, 1995; 2, Halvorson et al., 2002; 3, Liebig et al., 2004; 4, Lyon et al., 1997; 5, Halvorson et al., 1997; 6, Halvorson et al., 1999; 7, Bowman et al., 1999; 8, Peterson and Westfall, 1997; 9, Potter et al., 1998.

‡ Discontinued.

Effects of tillage on SOC in the region indicate no-till (NT) is effective at either increasing SOC or mitigating SOC loss, but under continuous cropping only (Table 6–3). Change in SOC under NT continuous cropping ranged from −0.05 to 0.23 Mg C ha^{-1} yr^{-1} for time-series data (Montana, North Dakota, Colorado), and 0.16 to 0.56 Mg C ha^{-1} yr^{-1} for data where a tilled treatment was used as a baseline for comparison (Texas). Continuous cropping systems utilizing minimum tillage (MT) generally resulted in decreased SOC, though a slight (0.03 Mg C ha^{-1} yr^{-1}) increase in SOC under MT was observed in North Dakota. At only one site did a cropping system utilizing conventional tillage (CT) increase SOC in the region. Potter (2006) observed SOC accrual from 0.13 to 0.16 Mg C ha^{-1} yr^{-1} under CT on a previously degraded clay soil near Temple, Texas.

Intensification of dryland cropping systems through the reduction of fallow increases input of above- and belowground biomass to the soil (Varvel et al., 2006). This, in turn, can increase SOC in near-surface depths (McVay et al., 2006; Mikha et al., 2006). For long-term experimental sites summarized in Table 6–3, SOC either increased or SOC loss was mitigated when the frequency of fallow was reduced. Within cropping systems managed under NT, change in SOC was positively associated with cropping frequency in the region ($r = 0.75$; $p = 0.0005$; $n = 17$; time-series data only). Changes in SOC from converting crop–fallow to continuous cropping under NT increased SOC accrual by 0.28 ± 0.16 Mg C ha^{-1} yr^{-1} ($n = 5$). In an evaluation near Akron, Colorado, continuous cropping increased SOC by 0.12 Mg C ha^{-1} yr^{-1} compared to cropping systems with fallow, regardless of tillage system used (Bowman et al., 1999). In Texas, a continuously cropped system with a 4-yr pasture phase under CT resulted in a slight gain in SOC (0.03 Mg C ha^{-1} yr^{-1}) over a similar cropping system without a pasture phase (Potter, 2006).

Climatic factors can influence the effectiveness of management practices to induce change in SOC (Burke et al., 1989). Peterson and Westfall (1997) established three long-term research sites in eastern Colorado representing a potential evapotranspiration (PET) gradient from north to south to quantify relationships among climate, soil type, and cropping sequence on agronomic and environmental attributes. After 12 yr of NT and continuous cropping, SOC increased from 0.05 to 0.12 Mg C ha^{-1} yr^{-1} across the three sites, with greater SOC accrual at the low (Sterling) and medium (Stratton) PET sites compared to the high (Walsh) PET site (Table 6–3). Across the research sites, annualized stover biomass explained 80% of the variation in SOC at 0 to 10 cm (Sherrod et al., 2003).

Long-term experiments evaluating application of crop nutrients in the region was limited to N fertilization treatments (Table 6–3). In eastern Colorado, Halvorson et al. (1999) observed SOC to increase from 0.09 to 0.18 Mg C ha^{-1} yr^{-1} with increasing N rate under continuous cropping relative to a 0 kg N ha^{-1} treatment. The effect of N fertilization on SOC in other long-term experiments, however, has been far from conclusive. Nitrogen fertilization did not affect SOC over 10 yr in dryland cropping systems near Bushland and Temple, Texas (Potter et al., 1997, 1998), and no difference in SOC was observed after 12 yr in spring wheat–fallow and spring wheat–winter wheat–sunflower cropping systems fertilized at high (45–101 kg N ha^{-1} yr^{-1}), medium (22–67 kg N ha^{-1} yr^{-1}), and low (0–34 kg N ha^{-1} yr^{-1}) rates of N fertilization in central North Dakota (Halvorson et al., 2002) (data not shown). These results contrast to those from the Canadian prairies, where VandenBygaart et al. (2003) found application of varying rates of fertilizer N increased SOC by 0.23 ± 0.13 Mg C ha^{-1} yr^{-1}.

Table 6–3. Changes in soil organic carbon (SOC) within dryland cropping systems as influenced by tillage, cropping intensity, and application of crop nutrients.

Location	Latitude, Longitude	MAAT†	MAP‡	Textural class	Depth	Management practices§	Duration	SOC change¶	Reference#
		°C	cm		cm		yr	Mg C ha^{-1} yr^{-1}	
					Tillage				
Culbertson, MT	48°33′, 104°50′	6.1	34	SL	0–20	SW-F, CT	21	(0.35)	1
Culbertson, MT	48°33′, 104°50′	6.1	34	SL	0–20	SW-B/SW-P, CT	21	(0.19)	1
Culbertson, MT	48°33′, 104°50′	6.1	34	SL	0–20	Cont. SW, CT	21	(0.10)	1
Culbertson, MT	48°33′, 104°50′	6.1	34	SL	0–20	Cont. SW, MT	21	(0.08)	1
Culbertson, MT	48°33′, 104°50′	6.1	34	SL	0–20	Cont. SW, NT	21	(0.05)	1
Mandan, ND	46°46′,100°57′	5.0	40	SiL	0–15.2	SW-F, CT	12	(0.27)	2
Mandan, ND	46°46′,100°57′	5.0	40	SiL	0–15.2	SW-F, MT	12	(0.15)	2
Mandan, ND	46°46′,100°57′	5.0	40	SiL	0–15.2	SW-F, NT	12	(0.32)	2
Mandan, ND	46°46′,100°57′	5.0	40	SiL	0–15.2	SW-WW-SF, CT	12	(0.14)	2
Mandan, ND	46°46′,100°57′	5.0	40	SiL	0–15.2	SW-WW-SF, MT	12	0.03	2
Mandan, ND	46°46′,100°57′	5.0	40	SiL	0–15.2	SW-WW-SF, NT	12	0.23	2
Sidney, NE	41°13′, 103°01′	9.0	45	SiL	0–30.5	Prev. cultivated, WW-F, CT	27	(0.53)	3
Sidney, NE	41°13′, 103°01′	9.0	45	SiL	0–30.5	Prev. cultivated, WW-F, MT	27	(0.51)	3
Sidney, NE	41°13′, 103°01′	9.0	45	SiL	0–30.5	Prev. cultivated, WW-F, NT	27	(0.43)	3

Table continued.

Table 6–3. Continued.

Location	Latitude, Longitude	MAAT†	MAP‡	Textural class	Depth	Management practices§	Duration	SOC change¶	Reference#
		°C	cm		cm		yr	Mg C ha^{-1} yr^{-1}	
Sidney, NE	41°13′, 103°01′	9.0	45	L	0–30.5	Native sod, WW-F, CT	22	(0.49)	3
Sidney, NE	41°13′, 103°01′	9.0	45	L	0–30.5	Native sod, WW-F, MT	22	(0.43)	3
Sidney, NE	41°13′, 103°01′	9.0	45	L	0–30.5	Native sod, WW-F, NT	22	(0.39)	3
Bushland, TX	35°11′, 102°5′	14.0	47	CL	0–20	Cont. crop, NT	10	0.42#	4
Temple, TX	31°03′, 97°20′	19.5	86	C	0–20	WW-SG-C, NT	10	0.16#	4
				Cropping Intensity					
Sterling, CO	40°37′, 103°13′	9.3	44	L	0–10	SW-F, NT	12	(0.09)	5
Sterling, CO	40°37′, 103°13′	9.3	44	L	0–10	SW-C-F, NT	12	(0.10)	5
Sterling, CO	40°37′, 103°13′	9.3	44	L	0–10	SW-C-M-F, NT	12	(0.04)	5
Sterling, CO	40°37′, 103°13′	9.3	44	L	0–10	Cont. crop, NT	12	0.12	5
Stratton, CO	39°18′, 102°26′	10.8	42	L	0–10	SW-F, NT	12	(0.09)	5
Stratton, CO	39°18′, 102°26′	10.8	42	L	0–10	SW-C-F, NT	12	0.03	5
Stratton, CO	39°18′, 102°26′	10.8	42	L	0–10	SW-C-M-F, NT	12	0.07	5
Stratton, CO	39°18′, 102°26′	10.8	42	L	0–10	Cont. crop, NT	12	0.11	5
Walsh, CO	37°23′, 102°17′	12.2	40	SCL	0–10	SW-F, NT	12	(0.09)	5
Walsh, CO	37°23′, 102°17′	12.2	40	SCL	0–10	SW-C-F, NT	12	(0.02)	5
Walsh, CO	37°23′, 102°17′	12.2	40	SCL	0–10	SW-C-M-F, NT	12	0.00	5
Walsh, CO	37°23′, 102°17′	12.2	40	SCL	0–10	Cont. crop, NT	12	0.05	5

Location	Latitude, Longitude	MAAT†	MAP‡	Textural class	Depth	Management practices§	Duration	SOC change¶	Reference#
		°C	cm		cm		yr	Mg C ha^{-1} yr^{-1}	
Akron, CO	40°09′, 103°08′	9.3	42	L	0–15	Plots with F	4	0.18	6
Akron, CO	40°09′, 103°08′	9.3	42	L	0–15	Plots without F	4	0.30	6
Bushland, TX	35°11′, 102°5′	14.0	47	CL	0–20	WW-F, NT	10	0.24††	7
Bushland, TX	35°11′, 102°5′	14.0	47	CL	0–20	WW-SG-F, NT	10	0.36††	7
Bushland, TX	35°11′, 102°5′	14.0	47	CL	0–20	Cont. SG, NT	10	0.28††	7
Bushland, TX	35°11′, 102°5′	14.0	47	CL	0–20	Cont. WW, NT	10	0.56††	7
Temple, TX	31°03′, 97°20′	19.5	86	C	0–30	Cont. crop, CT without pasture phase	55	0.13	8
Temple, TX	31°03′, 97°20′	19.5	86	C	0–30	Cont. crop, CT with 4-yr pasture phase	55	0.16	8
Application of Crop Nutrients									
Akron, CO	40°09′, 103°08′	9.3	42	SiL	0–15	B-C-O/P, 45 kg N ha^{-1}	11	0.09‡‡	9
Akron, CO	40°09′, 103°08′	9.3	42	SiL	0–15	B-C-O/P, 67 kg N ha^{-1}	11	0.14‡‡	9
Akron, CO	40°09′, 103°08′	9.3	42	SiL	0–15	B-C-O/P, 134 kg N ha^{-1}	11	0.18‡‡	9

† MAAT, mean annual air temperature.

‡ MAP, mean annual precipitation.

§ B, barley; C, corn; Cont., continuous; CT, conventional tillage; F, fallow; M, millet; MT, minimum tillage; NT, no-tillage; O, oat; P, pea; Prev., previous; SF, sunflower; SG, sorghum; SW, spring wheat; WW, winter wheat.

¶ Values in parentheses indicate SOC loss.

1, Sainju et al., 2007; 2, Halvorson et al., 2002; 3, Doran et al., 1998; 4, Potter et al., 1998; 5, Sherrod et al., 2003; 6, Bowman et al., 1999; 7, Potter et al., 1997; 8, Potter, 2006; 9, Halvorson et al., 1999.

†† SOC change relative to MT treatment, 1998.

‡‡ SOC change relative to B-C-O/P, 0 kg N ha^{-1}.

Implications of Improved Management

Agroecosystem Performance

The significance of increased SOC storage extends beyond the role of soil as a repository for excess atmospheric C. Accrual of SOC in agricultural lands is associated with changes in soil physical, chemical, and biological attributes that affect key soil functions, such as nutrient cycling, filtering and buffering capacity, and regulation of water flow (Andrews et al., 2004; Janzen, 2005). Increases in SOC from improved management are generally regarded to enhance agroecosystem performance over time (Lal, 2002), though such a relationship is difficult to quantify precisely. The integral nature of SOC as a key contributor of agroecosystem health has prompted scientists to consider its role as an indicator more broadly, one in which change in SOC can be used as a surrogate for ecosystem stability and/or agricultural sustainability (Doran, 2002; Janzen, 2005).

For dryland cropping systems in the U.S. Great Plains, associations between SOC change and agroecosystem performance are often difficult to detect in the short term, given the low production levels and high climatic variability. Recent efforts by Wienhold et al. (2006), however, sought to quantify such associations using recently developed assessment tools for evaluating the effects of management systems on agronomic and environmental soil functions. In their evaluation, they observed positive correlations ($r \geq 0.70$; $p \leq 0.035$) between SOC at 0 to 15 cm and Soil Management Assessment Framework (SMAF) index scores in four of eight long-term cropping system experiments in the Great Plains. Greater index scores from SMAF are indicative of improved soil function (Andrews et al., 2004), which in the evaluation by Wienhold et al. was associated with increased agronomic yield.

The relationship between SOC and crop yield has been inferred since ancient times in the writings of Roman philosophers (Harrison, 1913). Quantification of such a relationship is challenging due to the innumerable interactions among biomass production and management variables, inherent soil attributes, land use history, and climate. Consequently, few attempts at defining a relationship between SOC and crop yield in semiarid cropping systems have been conducted. In a study evaluating the differential effects of SOC on crop productivity in central North Dakota, Bauer and Black (1994) found spring wheat grain yield to increase by 16 kg ha^{-1} with each 1 Mg ha^{-1} increase in soil organic matter (SOM) across a range of 64 to 142 Mg SOM ha^{-1}. Similarly, Diaz-Zorita et al. (1999) found the contribution of 1 Mg SOM ha^{-1} to be equivalent to approximately 40 kg wheat grain ha^{-1} in an evaluation of 134 farmer fields in the semiarid Argentine Pampas. In their evaluation (Diaz-Zorita et al., 1999) and the evaluations of others (Janzen et al., 1992), grain and/or dry matter yield increased with increasing SOC to an upper threshold, after which additional SOC had no affect on crop yield. These results underscore the important contribution of SOC to agronomic productivity in semiarid cropping systems but reflect that the relationship is site specific and not linear.

Carbon Trading and Exchange Offsets

In addition to potential on-site improvements in soil quality and crop productivity from increased SOC storage, agricultural producers can earn additional income through involvement in carbon trading programs when they follow

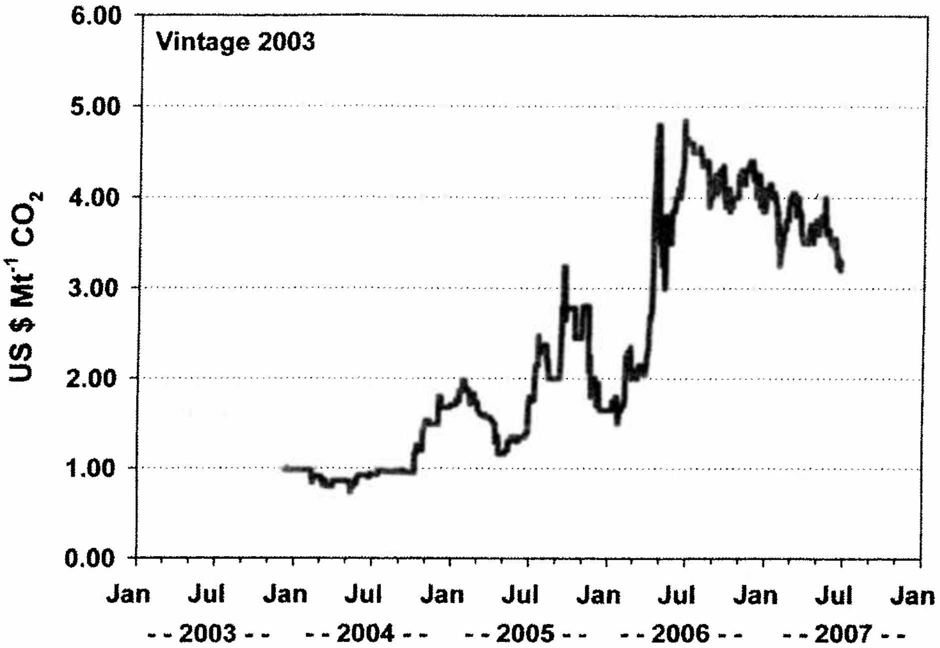

Fig. 6–3. Market value of CO_2 traded on the Chicago Climate Exchange, December 2003 to May 2007. (Chicago Climate Exchange, 2007.)

prescribed management practices known to sequester SOC. Such programs provide a framework for multinational corporations, utility and power generation companies, and other private and public organizations to offset their CO_2 emissions by purchasing carbon credits from entities known to achieve net C storage. The Chicago Climate Exchange (CCX) administers transfer of carbon credits through an established set of rules allowing GHG benefits from conservation practices to be quantified, credited, and sold. Credits transferred by CCX are aggregated from multiple agricultural producers and/or landowners to sell them to CCX members that have made voluntary commitments to reduce their GHG emissions. The CCX is the world's first and North America's only legally binding rules-based GHG emissions allowance trading program, as well as the world's only global system for emissions trading for six GHGs (CO_2, CH_4, N_2O, sulfur hexafluoride, perfluorocarbons, and hydrofluorocarbons) (Chicago Climate Exchange, 2007).

The CCX program, while voluntary, has achieved considerable success in North America. Since CCX began GHG emissions trading in 2003, approximately six million acres of approved conservation practices have been enrolled in carbon credit programs throughout the United States and Canada (Dale Enerson, personal communication, 2007). In North Dakota alone, more than 323,000 ha of continuous NT and permanent grass were enrolled in the North Dakota Farmers Union Carbon Credit Program in 2006 (North Dakota Union Farmer, 2007). Since 2003, the market value of CO_2 traded on the CCX has increased from \$0.90 to \$3.30 Mg^{-1} CO_2 (Fig. 6–3). Carbon offset rates established by CCX for approved cropland practices (continuous conservation tillage) range from 0.49 to 1.48 Mg CO_2 ha^{-1} yr^{-1} (0.2 to 0.6 Mg CO_2 ac^{-1} yr^{-1}), providing approximately \$1.46 to \$4.40 ha^{-1} yr^{-1} in additional farm income based on the current market value of CO_2 (assuming \$3.30 Mg^{-1} CO_2 minus a 10% aggregator service fee). Though remuneration is currently modest on a per acre basis, the supplementary income generated from enrollment in carbon credit programs can provide a significant revenue source for large landholders.

Carbon trading of agricultural offsets is likely to expand in the future. On 2 Apr. 2007, the U.S. Supreme Court declared the U.S. Environmental Protection Agency must regulate GHG emissions as pollutants under the Clean Air Act (U.S. Supreme Court, 2006). Should GHG emissions reductions be mandated by future legislation, there will be increased demand for emission offsets from agriculture. With this increased demand, carbon offsets will undergo greater scrutiny to ensure emission reduction benefits are achieved (Schlesinger, 2006). For agroecosystems, this may translate to more inclusive assessments of GHG emissions when determining appropriate carbon offset values. For instance, instead of using only estimates of SOC change across time to determine offset values (as currently done), GHG emissions from all sources of production (farm operations, N fertilizer production, etc.), as well as CH_4 and N_2O flux, will need to be considered to arrive at an overall assessment of global warming potential (GWP) for specific management practices. Comprehensive evaluations such as this will not only alter carbon offset values for agroecosystems, but will change the portfolio of accepted land management practices in carbon credit programs.

Greenhouse Gas Balance

Mitigation of GHGs from agroecosystems requires adoption of management practices that minimize the increase in atmospheric radiative forcing. Radiative forcing refers to the change in the net vertical irradiance at the tropopause due to an internal change or a change in the external forcing of the climate system, such as, for example, a change in the concentration of CO_2 or in the output of the sun (IPCC, 2007). Appraisals of agroecosystem impacts on radiative forcing require determinations of not only SOC accrual or loss, but of CH_4 and N_2O flux as well. Storage of atmospheric CO_2 into stable forms of SOC can sequester CO_2, while typical crop production practices generate N_2O emission and decrease the soil sink for atmospheric CH_4 (Mosier et al., 2003). Collectively, the balance of the net exchange of CO_2, CH_4, and N_2O from an agroecosystem constitutes its net GWP (Robertson et al., 2000), which represents the combined effect of these gases to remain in the atmosphere and absorb outgoing infrared radiation (IPCC, 2007).

Studies in the U.S. Great Plains documenting the effects of dryland cropping systems on GHG flux are lacking. Mosier et al. (2003) presented preliminary results from a 1-yr evaluation in northeast Colorado, where continuous cropping treatments possessed a net negative GWP (net CO_2 uptake), while cropping treatments including fallow possessed a net positive GWP (net CO_2 loss). Methane and N_2O fluxes did not differ between cropping systems in their evaluation, making management impacts on SOC the driving factor in determining net GWP. Generally, dryland cropping systems are minor sinks for atmospheric CH_4 and moderate sources of N_2O, depending largely on the amount of N fertilizer applied (Liebig et al., 2005).

In most agroecosystems, the relationship between SOC change to N_2O emission regulates net GWP (Robertson et al., 2000). In this regard, data from Table 6–3 were used to calculate rates of N_2O emission from dryland cropping systems resulting in a neutral net GWP, thereby negating CO_2 sequestered as SOC after accounting for CO_2 uptake and release (expressed as CO_2 equivalents) associated

Table 6–4. Calculated rates of N_2O emission to achieve neutral net global warming potential (GWP) for no-till continuous-cropping management systems in the U.S. Great Plains.

Location	SOC accrual†	CH_4 uptake‡	N fertilizer production§	Farm operations¶		Calculated N_2O emission to achieve neutral GWP
	kg CO_2 equivalents ha^{-1} yr^{-1}					g N ha^{-1} d^{-1}
Mandan, ND	−843	−46	247	85	558	3.3
Sterling, CO	−440	−46	383	85	18	0.1
Stratton, CO	−403	−46	383	85	−18	–
Walsh, CO	−183	−46	383	85	−238	–
Bushland, TX	−1540	−46	115	85	1386	8.1
Temple, TX	−587	−46	298	85	250	1.5

† SOC, soil organic carbon; accrual values taken from Table 6–3 after conversion to kg CO_2 equivalents (Mg C ha^{-1} yr^{-1} × 1000 × 44/12); negative numbers imply CO_2 uptake; positive numbers imply CO_2 release.

‡ CH_4 uptake rate for dryland cropping systems taken from Liebig et al. (2005); conversion factors to CO_2 equivalents for CH_4 and N_2O were 25 and 298, respectively (IPCC, 2007).

§ CO_2 equivalents for N-fertilizer production based on published rates of N fertilization at experimental sites and estimated energy use to produce (0.82 kg CO_2-C kg^{-1} N) (Follett, 2001) and apply (45.5 kg CO_2 ha^{-1}) (West and Marland, 2002) fertilizer N.

¶ CO_2 equivalents for farm operations adapted from Mosier et al. (2003).

with farm operations, N fertilizer production, and CH_4 flux. Only continuous cropping systems under NT management with documented SOC accrual over time were considered (i.e., Mandan, Sterling, Stratton, Walsh, Bushland, Temple). Results from this exercise indicated practices at four sites could emit 0.1 to 8.1 g N_2O N ha^{-1} d^{-1} and maintain a neutral GWP (Table 6–4). Two sites (Stratton and Walsh) were estimated to have net positive GWP before accounting for N_2O emission, where a net positive GWP implies an increase in atmospheric radiative forcing. It is important to note, however, that with the possible exception of Bushland, all sites would likely possess a net positive GWP, as N_2O emission has been found to average 3.7 g N_2O N ha^{-1} d^{-1} for dryland cropping systems with N fertilization levels exceeding 50 kg N ha^{-1} (Liebig et al., 2005). Though calculations in this exercise are approximations only, the results underscore the importance of (i) accounting for all GHG sources and sinks for estimating the impact of agroecosystems on radiative forcing and, more specifically, (ii) optimizing N management in dryland cropping systems to minimize N_2O emission. As pointed out by Six et al. (2004), the effectiveness of NT cropping systems to reduce atmospheric radiative forcing is associated with the adoption of specific management practices that increase SOC while concurrently minimizing N_2O emission.

Conclusions

The purpose of this chapter was to provide a synopsis of management effects on SOC for dryland cropping systems in the U.S. Great Plains. Data from long-term experiments in the region indicate management practices capable of either increasing SOC or mitigating SOC loss included adoption of NT, increased cropping intensity, and improved soil fertility. Cropping systems characterized by continuous cropping under NT management possessed the greatest potential for accruing SOC in the region. Concomitant benefits from SOC accrual in dryland cropping systems include improvements in soil quality and crop productivity, and more recently, offset payments from industry to agricultural producers through involvement in carbon trading programs. Though continuous cropping NT management systems appear effective at sequestering SOC in the region, presumptions regarding the capacity of this practice to reduce atmospheric radiative forcing are tenuous, owing mainly to uncertainties associated with the contribution of N_2O emission on net GWP.

Acknowledgments

We thank the numerous individuals who established and maintained long-term cropping system experiments in the U.S. Great Plains. We also thank Ardell Halvorson and Upendra Sainju for their helpful suggestions to improve an earlier version of this manuscript. This publication is based on work supported by the Agricultural Research Service under the ARS GRACEnet Project. The U.S. Department of Agriculture, Agricultural Research Service is an equal opportunity/affirmative action employer and all agency services are available without discrimination.

References

Aandahl, A.R. 1972. Soil of the Great Plains. 1/2,500,000 scale map. USDA-SCS and Univ. of Nebraska, Lincoln.

Andrews, S.S., D.L. Karlen, and C.A. Cambardella. 2004. The soil management assessment framework: A quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68:1945–1962.

Aneja, V.P., W.H. Schlesinger, D. Niyogi, G. Jennings, W. Gilliam, R.E. Knighton, C.S. Duke, J. Blunden, and S. Krishnan. 2006. Emerging national research needs for agricultural air quality. EOS 87(3):25, 29.

Bailey, R.G. 1995. Description of the ecoregions of the United States. USDA, Forest Service Misc. Publ. 1391, 2nd ed. U.S. Gov. Print. Office, Washington, DC.

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185–193.

Bowman, R.A., J.D. Reeder, and R.W. Lober. 1990. Changes in soil properties in a central plains rangeland soil after 3, 20, and 60 years of cultivation. Soil Sci. 150:851–857.

Bowman, R.A., M.J. Vigil, D.C. Nielsen, and R.L. Anderson. 1999. Soil organic matter changes in intensively cropped dryland systems. Soil Sci. Soc. Am. J. 63:186–191.

Bronson, K.F., T.M. Zobeck, T.T. Chua, V. Acosta-Martinez, R.S. van Pelt, and J.D. Booker. 2004. Carbon and nitrogen pools of southern High Plains cropland and grassland soils. Soil Sci. Soc. Am. J. 68:1695–1704.

Brown, L.R. 2006. Plan B 2.0: Rescuing a planet under stress and a civilization in trouble. W.W. Norton and Company, New York.

Burke, I.C., C.M. Yonker, W.J. Parton, C.V. Cole, K. Flach, and D.S. Schimel. 1989. Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. Soil Sci. Soc. Am. J. 53:800–805.

Chicago Climate Exchange. 2007. Overview. Available at http://www.chicagoclimateexchange.com (verified 22 June 2007).

Cihacek, L.J., and M.G. Ulmer. 1995. Estimated soil organic carbon losses from long-term crop-fallow in the northern Great Plains of the USA. p. 85–92. *In* R. Lal et al. (ed.) Soil management and greenhouse effect. Lewis Publ., Boca Raton, FL.

Diaz-Zorita, M., D.E. Buschiazzo, and N. Peinemann. 1999. Soil organic matter and wheat productivity in the semiarid Argentine Pampas. Agron. J. 91:276–279.

Donigian, A.S., Jr., T.O. Barnwell, R.B. Jackson, A.S. Parwardhan, K.B. Weinreich, A.L. Rowell, R.V. Chinnaswamy, and C.V. Cole. 1994. Assessment of alternative management practices and policies affecting soil carbon in agroecosystems of the central United States. Publ. No. EPA/600/R-94/067. U.S. Environmental Protection Agency, Athens, GA.

Doran, J.W. 2002. Soil health and global sustainability: Translating science into practice. Agric. Ecosyst. Environ. 88:119–127.

Doran, J.W., E.T. Elliott, and K. Paustian. 1998. Soil microbial activity, nitrogen cycling, and long-term changes in organic carbon pools as related to fallow tillage management. Soil Tillage Res. 49:3–18.

Follett, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Tillage Res. 61:77–92.

Franzluebbers, A.J., and R.F. Follett. 2005. Greenhouse gas contributions and mitigation potential in agricultural regions of North America. Introduction. Soil Tillage Res. 83:1–8.

Haas, H.J., C.E. Evans, and E.F. Miles. 1957. Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments. Tech. Bull. No. 1164, USDA. U.S. Gov. Print. Office, Washington, DC.

Halvorson, A.D., C.A. Reule, and R.F. Follett. 1999. Nitrogen fertilization effects on soil carbon and nitrogen in a dryland cropping system. Soil Sci. Soc. Am. J. 63:912–917.

Halvorson, A.D., M.F. Vigil, G.A. Peterson, and E.T. Elliott. 1997. Long-term tillage and crop residue management study at Akron, Colorado. p. 361–370. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Halvorson, A.D., B.J. Wienhold, and A.L. Black. 2002. Tillage, nitrogen, and cropping system effects on soil carbon sequestration. Soil Sci. Soc. Am. J. 66:906–912.

Harrison, F. 1913. Roman farm management: The treatises of Cato and Varro. Macmillin, New York.

Hide, J.C., and W.H. Metzger. 1939. The effect of cultivation and erosion on the nitrogen and carbon of some Kansas soils. Agron. J. 31:625–632.

Hobbs, J.A., and P.L. Brown. 1965. Effects of cropping and management on nitrogen and organic carbon contents of a western Kansas soil. Kansas State Univ. of Agric. and Appl. Sci. Tech. Bull. No. 144. Kansas State Univ., Manhattan.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate change 2007: The physical science basis. 4th Assessment Report. Available at http://www.ipcc.ch (verified 20 Apr. 2007).

Janzen, H.H. 2005. Soil carbon: A measure of ecosystem response in a changing world? Can. J. Soil Sci. 85:467–480.

Janzen, H.H., C.A. Campbell, R.C. Izaurralde, B.H. Ellert, N. Juma, W.B. McGill, and R.P. Zentner. 1998. Management effects on soil C storage on the Canadian prairies. Soil Tillage Res. 47:181–195.

Janzen, H.H., F.J. Larney, and B.M. Olson. 1992. Soil quality factors of problem soils in Alberta. Proc. Alberta Soil Sci. Workshop, Lethbridge, AB, Canada.

Lal, R. 2002. Why carbon sequestration in agricultural soils. p. 21–30. *In* J.M. Kimble, R. Lal, and R.F. Follett (ed.) Agricultural practices and policies for carbon sequestration in soil. Lewis Publ., Boca Raton, FL.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627.

Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. 1999. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Ann Arbor Press, Chelsea, MI.

Liebig, M.A., J.A. Morgan, J.D. Reeder, B.H. Ellert, H.T. Gollany, and G.E. Schuman. 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. Soil Tillage Res. 83:25–52.

Liebig, M.A., D.L. Tanaka, and B.J. Wienhold. 2004. Tillage and cropping effects on soil quality indicators in the northern Great Plains. Soil Tillage Res. 78:131–141.

Lyon, D.J., C.A. Monz, R.E. Brown, and A.K. Metherell. 1997. Soil organic matter changes over two decades of winter wheat–fallow cropping in western Nebraska. p. 343–351. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Mahlman, J.D. 1997. Uncertainties in projections of human-caused climate warming. Science 278:746–1417.

Matson, P.A., W.J. Parton, A.G. Power, and M.J. Swift. 1997. Agricultural intensification and ecosystem properties. Science 277:504–509.

McVay, K.A., J.A. Budde, K. Fabrizzi, M.M. Mikha, C.W. Rice, A.J. Schlegel, D.E. Peterson, D.W. Sweeney, and C. Thompson. 2006. Management effects on soil physical properties in long-term tillage studies in Kansas. Soil Sci. Soc. Am. J. 70:434–438.

Mikha, M.M., M.F. Vigil, M.A. Liebig, R.A. Bowman, B. McConkey, E.J. Deibert, and J.L. Pikul, Jr. 2006. Cropping system influences on soil chemical properties and soil quality in the Great Plains. Renew. Agric. Food Syst. 20:26–35.

Mosier, A.R., G.A. Peterson, and L.A. Sherrod. 2003. Mitigating net global warming potential (CO_2, CH_4, and N_2O) in upland crop production. Proc. 3rd Int. Methane and Nitrous Oxide Mitigation Conf., 17–21 Nov. 2003, Beijing, China.

National Agricultural Statistics Service. 2007. 2002 Census of agriculture: Vol. 1, Geographic area series. Available at http://www.nass.usda.gov/Data_and_Statistics/index.asp (verified 24 Apr. 2007).

North Dakota Union Farmer. 2007. First North Dakota carbon credits sold on Chicago Climate Exchange. 54(1):7.

Oreskes, N. 2004. The scientific consensus on climate change. Science 306:1686.

Padbury, G.A. 2003. Agroecosystems of the Canadian Great Plains. p. 9–19. *In* J.D. Hanson and J.M. Krupinsky (ed.) Proc. of Dynamic Cropping Systems: Principles, Processes, and Challenges (CD-ROM), Bismarck, ND, 5–7 Aug. 2003. USDA-ARS Northern Great Plains Research Laboratory, Mandan, ND.

Padbury, G., S. Waltman, J. Caprio, G. Coen, S. McGinn, D. Mortensen, G. Nielsen, and R. Sinclair. 2002. Agroecosystems and land resources of the northern Great Plains. Agron. J. 94:251–261.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9:180–186.

Peterson, G.A., and D.G. Westfall. 1997. Management of dryland agroecosystems in the central Great Plains of Colorado. p. 371–380. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Pikul, J.L., and J.K. Aase. 1995. Infiltration and soil properties as affected by annual cropping in the northern Great Plains. Agron. J. 87:656–662.

Potter, K.N. 2006. Soil carbon content after 55 years of management of a Vertisol in central Texas. J. Soil Water Conserv. 61:338–343.

Potter, K.N., O.R. Jones, H.A. Torbert, and P.W. Unger. 1997. Crop rotation and tillage effects on organic carbon sequestration in the semiarid southern Great Plains. Soil Sci. 162:140–147.

Potter, K.N., H.A. Torbert, O.R. Jones, J.E. Matocha, J.E. Morrison, Jr., and P.W. Unger. 1998. Distribution and amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47:309–321.

Richter, D.deB., M. Hofmockel, M.A. Callaham, Jr., D.S. Powlson, and P. Smith. 2007. Long-term soil experiments: Keys to managing Earth's rapidly changing ecosystems. Soil Sci. Soc. Am. J. 71:266–279.

Robertson, G.P., E.A. Paul, and R.R. Harwood. 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. Science 289:1922–1925.

Rosenzweig, C., and D. Hillel. 1998. Climate change and the global harvest: Potential impacts of the greenhouse effect on agriculture. Oxford Univ. Press, Oxford, UK.

Russel, J.C. 1929. Organic matter problems under dry-farming conditions. J. Am. Soc. Agron. 21:960–969.

Sainju, U.M., T. Thecan-Thonthat, A.W. Lenssen, R.G. Evans, and R. Kolberg. 2007. Long-term tillage frequency and cropping intensity effects on dryland residue and soil carbon fractions. Soil Sci. Soc. Am. J. 71(6):1730–1739 .

Schlesinger, W.H. 2006. Carbon trading. Science 314:1217.

Sherrod, L.A., G.A. Peterson, D.G. Westfall, and L.R. Ahuja. 2003. Cropping intensity enhances soil organic carbon and nitrogen in a no-till agroecosystem. Soil Sci. Soc. Am. J. 67:1533–1543.

Six, J., S.M. Ogle, F.J. Breidt, R.T. Conant, A.R. Mosier, and K. Paustian. 2004. The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term. Global Change Biol. 10:155–160.

Soil Survey Staff. 1981. Land resource regions and major land resource areas of the United States. USDA-SCS Agric. Handbook No. 296, Rev. Ed. U.S. Gov. Print. Office, Washington, DC.

Soil Survey Staff. 1999. Soil taxonomy, 2nd ed. USDA-NRCS, U.S. Dep. of Agric. Handbook No. 436. U.S. Gov. Print. Office, Washington, DC.

Tanaka, D.L., J.M. Krupinsky, S.D. Merrill, M.A. Liebig, and J.D. Hanson. 2007. Dynamic cropping systems for sustainable crop production in the northern Great Plains. Agron. J. 99:904–911.

U.S. Census Bureau. 2007. The 2007 statistical abstract. Available at http://www.census.gov/compendia/statab/ (verified 23 Apr. 2007).

U.S. Supreme Court. 2006. 2006 term opinions of the court: Massachusetts vs. EPA. Available at http://www.supremecourtus.gov/opinions/06pdf/05-1120.pdf (verified 4 May 2007).

VandenBygaart, A.J., E.G. Gregorich, and D.A. Angers. 2003. Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies. Can. J. Soil Sci. 83:363–380.

Varvel, G., W. Riedell, E. Deibert, B. McConkey, D. Tanaka, M. Vigil, and R. Schwartz. 2006. Great Plains cropping system studies for soil quality assessment. Renew. Agric. Food Syst. 21:3–14.

West, T.O., and G. Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91:217–232.

Westfall, D.G., J.L. Havlin, G.W. Hergert, and W.R. Raun. 1996. Nitrogen management in dryland cropping systems. J. Prod. Agric. 9:192–199.

Wienhold, B.J., J.L. Pikul, Jr., M.A. Liebig, M.M. Mikha, G.E. Varvel, J.W. Doran, and S.S. Andrews. 2006. Cropping system effects on soil quality in the Great Plains: Synthesis from a regional project. Renew. Agric. Food Syst. 20:49–59.

Zhang, G., Z. Zhang, and J. Liu. 2001. Spatial distribution of Aeolian erosion of soil and its driving factors in China. Acta Geogr. Sin. 56:146–158.