Available online at www.sciencedirect.com
SCIENCE DIRECT®

Soil & Tillage Research 83 (2005) 73–94

Soil & Tillage Research

www.elsevier.com/locate/still

Review

Greenhouse gas contributions and mitigation potential of agriculture in the central USA

J.M.F. Johnson [a,*], D.C. Reicosky [a], R.R. Allmaras [b], T.J. Sauer [c], R.T. Venterea [b], C.J. Dell [d]

[a] *USDA-ARS, North Central Soil Conservation Research Laboratory, 803 Iowa Ave., Morris, MN 56267, USA*
[b] *USDA-ARS, Department of Soil, Water and Climate, University of Minnesota, St. Paul, MN 55108, USA*
[c] *USDA-ARS, Soil Tilth Laboratory, 2150 Pammel Dr., Ames, IA 50011-3120, USA*
[d] *USDA-ARS, Curtin Rd., Bldg. 3702, University Park, PA 16802-3702, USA*

Received 21 April 2004; received in revised form 6 January 2005

Abstract

The central USA contains some of the most productive agricultural land of the world. Due to the high proportion of land area committed to crops and pasture in this region, the carbon (C) stored and greenhouse gas (GHG) emission due to agriculture represent a large percentage of the total for the USA. Our objective was to summarize potential soil organic C (SOC) sequestration and GHG emission from this region and identify how tillage and cropping system interact to modify these processes. Conservation tillage (CST), including no-tillage (NT), has become more widespread in the region abating erosion and loss of organic rich topsoil and sequestering SOC. The rate of SOC storage in NT compared to conventional tillage (CT) has been significant, but variable, averaging 0.40 ± 0.61 Mg C ha^{-1} year^{-1} (44 treatment pairs). Conversion of previous cropland to grass with the conservation reserve program increased SOC sequestration by 0.56 ± 0.60 Mg C ha^{-1} year^{-1} (five treatment pairs). The relatively few data on GHG emission from cropland and managed grazing land in the central USA suggests a need for more research to better understand the interactions of tillage, cropping system and fertilization on SOC sequestration and GHG emission.
© 2005 Elsevier B.V. All rights reserved.

Keywords: Carbon storage; Greenhouse gas; Carbon dioxide; Agriculture management; Managed grass land; Nitrous oxide

Contents

* Corresponding author. Tel.: +1 320 5893411x161.
E-mail address: jjohnson@morris.ars.usda.gov (J.M.F. Johnson).

0167-1987/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2005.02.010

1. Introduction

Agriculture provides both sources and sinks of greenhouse gas (GHG), which includes carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Global intensification of food and fiber production is an important factor influencing GHG emission. Generally, agriculture in the USA is thought of as a minor source (about 7%, Lal et al., 1998) of total global GHGs. However, increasing world population dictates a challenge to increase agricultural production without increasing GHG emission or environmental degradation. Management controls that interact with C storage and GHG emissions include crop type, fallow frequency, residue management, soil amendments, cover crops, rotations, tillage, irrigation, drainage, mulching and fertilization (Paustian et al., 1997). Management factors, such as tillage and land use change between cultivated and uncultivated conditions, contribute to the uncertainty in predicting whether change in agricultural land use between 1982 and 1997 in the USA was a net sink or net source for atmospheric C (Ogle et al., 2003). Therefore, it is important to understand how management and environment interact to sustain agricultural production and protect soil, water and air quality. Soil type and climate will either limit or focus the management options available that affect soil organic carbon (SOC) storage (Paustian et al., 1997) and GHG emission.

In the central USA, cropland and pasture are the major agricultural land uses (USDA-NRCS, 1997a). Small changes in SOC storage or GHG emission on a unit land area thus translate into a large regional/national contribution. Currently, there are few data that address how management changes in the central USA simultaneously impact SOC storage and GHG emission. This review addresses SOC storage and GHG emission from agricultural sources in the central USA, emphasizing SOC changes due to crop and tillage management and GHG emission associated with fertilizers and managed grasslands. We discuss the potential significance of GHG emission, as affected by tillage management, the main regulators of GHG emission and how these regulators may be influenced by reduced tillage on cropland. We also review what is known and identify future research needs for quantifying C storage and GHG emission in pastures in the central USA.

2. Characteristics of region

Geographically, the central USA for this review is defined to include the major portions of Illinois, Indiana, Iowa, Kentucky, Michigan, Missouri, Minnesota, Ohio, Pennsylvania, Tennessee, West Virginia and Wisconsin (Franzluebbers and Follett, 2005). Much of this region corresponds to the midwest US that encompasses the "Corn Belt". The Intergovernmental Panel for Climate Change (IPCC) descriptive code for this area is cold temperate, moist for the northern states and warm temperate, moist for the more southern areas (Eve et al., 2001). Mean annual precipitation increases from west to east across the region from 50 to 130 cm, and mean annual temperature increases north to south from 4 to 13 °C with maximum temperature and precipitation in the summer months, June–September (Owenby et al., 2001). The frost-free period ranges from <90 days at a few northern locations to >150 days at southern parts of the region (NCDC, 2001). The dominant cropping system changes from row crops in

Table 1
Ecoregion provinces, corresponding land-resource regions, major land resource areas and dominant soils of central USA

Ecoregion provinces[a]	Land resource region[b]	Major land resource area	Dominant soils
221 Eastern Broadleaf Forest (Oceanic)	K—northern lake states forest and forage region	95B—Southern Wisconsin and Northern Illinois Drift Plain	Udalfs
	N—East and central farming and forest region	111—Indiana and Ohio Till Plain	Udalfs, Aqualfs
		120—Kentucky and Indiana Sandstone and Shale Hills and Valleys	Udalfs
		121—Kentucky Bluegrass	Udalfs
		122—Highland Rim and Pennyroyal	Udalfs, Udulfs
		124—Western Allegheny Plateau	Ochrepts, Udults, Udalfs
		125—Cumberland Plateau and Mountains	Udults
		126—Central Allegheny Plateau	Udalfs, Udults, Ochrepts
		127—Eastern Allegheny Plateau and Mountains	Ochrepts, Udults, Aquults
		128—Southern Appalachian Ridges and Valleys	Udults, Ochrepts
	R—northeastern forage and forest region	139—Eastern Ohio Till Plain	Udalfs, Aqualfs
222 Eastern Broadleaf Forest (Continental)	L—lake states fruit, truck, and dairy region	97—Southwestern Michigan Fruit and Truck Belt	Udalfs
		98—Southern Michigan and Northern Indiana Drift Plain	Udalfs, Aqualfs
		99—Erie-Huron Lake Plain	Aqualfs, Aquepts
		100—Erie Fruit and Truck Area	Aquepts, Aqualfs
	M—central feed grains and livestock region	57—Northern Minnesota Gray Drift	Boralfs, Aqualfs, Fibrists
		88—Northern Minnesota Glacial Lake Basins	Aqualfs, Boralfs, Saprists, Fibrists
		105—Northern Mississippi Valley	Udalfs
		108—Illinois and Iowa Deep Loess and Drift	Udolls
		110—Northern Illinois and Indiana Heavy Till Plain	Udolls, Aquolls
		113—Central Claypan Areas	Aqualfs
		114—Southern Illinois and Indiana Thin Loess and Till Plain	Aqualfs
		115—Central Mississippi Valley Wooded Slopes	Udalfs
	N—east and central farming and forest region	116A—Ozark Highland	Udults, Udalfs
		116B—Ozark Border	Udalfs, Udults
		120—Kentucky and Indiana Sandstone and Shale Hills and Valleys	Udalfs
		122—Highland Rim and Pennyroyal	Udalfs, Udulfs
	R—northeastern forage and forest region	111—Indiana and Ohio Till Plain	Udalfs, Aqualfs
251 Prairie Parkland (Temperate)	F—northern great plains spring wheat region	56—Red River Valley of the North	Aquolls
	M—central feed grains and livestock region	102A—Rolling Till Prairie	Borolls
		103—Central Iowa and Minnesota Till Prairies	Udolls, Udalfs, Aqualfs, Aquolls
		104—Eastern Iowa and Minnesota Till Prairies	Udolls, Udalfs, Aquolls
		105—Northern Mississippi Valley	Udalfs
		107—Iowa and Missouri Deep Loess Hills	Udolls, Orthents

Table 1 (*Continued*)

Ecoregion provinces[a]	Land resource region[b]	Major land resource area	Dominant soils
		108—Illinois and Iowa Deep Loess and Drift	Udolls
		109—Iowa and Missouri Heavy Till Plain	Udolls
		112—Cherokee Prairies	Aqualfs, Udolls
		113—Central Claypan Areas	Aqualfs
		114—Southern Illinois and Indiana Thin Loess and Till Plain	Aqualfs
		115—Central Mississippi Valley Wooded Slopes	Udalfs

[a] Bailey (1995).
[b] USDA-NRCS (2001).

rotation with small grains (wheat, *Triticum aestivium* L; barley, *Hordeum vulgare* L.; oat, *Avena sativa* L.) and forages in the cool, moist sections to corn (*Zea mays* L.) and soybean (*Glycine max* L. Merrill) over much of the area from Ohio to Iowa and lower amount of row crops and greater amount of small grains in the drier western fringe adjoining the Plains States.

Bailey (1995) divided this region into three ecosystem provinces based primarily on native vegetation: 251 Prairie Parkland Temperate, 222 Eastern Broadleaf Forest Continental, and 221 Eastern Broadleaf Forest Oceanic. Within these ecoregions are a diverse group of land resource regions (LRR) and major land resource areas (MLRA; Table 1) defined by the United States Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS) that provide detailed information on soil and climate interaction related to crop production (Soil Survey Staff, 1981; USDA-NRCS, 1997b). Mollisols and Alfisols are the predominant soil orders throughout much of the region derived from glacial till or loess deposits and are some of the most productive soils of the world.

To supplement the description of MLRAs in the USA, Allmaras et al. (1991) defined tillage management regions (TMR) based on climate, topography, soils and land-use practices. The central USA includes three TMRs, the northern Corn Belt, the southern Corn Belt and portions of the Eastern Uplands. Allmaras et al. (1991, 1994) suggested that TMRs be delineated so that the technological problems and development of conservation tillage systems be more systematic. At present, there is no unified approach to describe agricultural cropping or tillage systems that address all biological, chemical and physical factors with respect to SOC sequestration, GHG emission and other issues of environmental quality. There is a need for a unifying system that integrates the relevant features of ecoregions, MLRAs, specific MLRA soils data, climate zones and TMRs. More emphasis on the role and type of C input within TMRs and MLRAs through crop selection and management eventually may lead to the development of C management regions.

3. Land use

The majority of the land in the central USA is cropland or forestland (Table 2) and except in Missouri, Tennessee and Kentucky pastureland represents 10% or less of the land use. Iowa, Illinois and Indiana have the largest percentage of their land area committed to cropland compared to other states in the central USA or within the USA. Corn and soybean are the principal crops and account for about 75% of total

Table 2
Percent of land use by state in the central USA and total for USA[a]

State	Cropland	Pastureland (%)	Forest land
Illinois	68	7	7
Indiana	59	8	17
Iowa	72	10	6
Kentucky	21	23	41
Michigan	24	6	44
Minnesota	42	7	32
Missouri	32	25	28
Ohio	45	8	27
Pennsylvania	19	6	54
Tennessee	18	19	45
West Virginia	6	10	68
Wisconsin	31	9	41
Total USA	20	6	21

[a] USDA-NRCS (1997a).

Table 3
Area of major crops grown in states from the central USA during 2003[a]

State	Total cropland	Corn[b]	Soybean (Mha)	Wheat	Hay
Illinois	9.3	4.5	4.2	0.3	0.3
Indiana	4.8	2.2	2.2	0.2	0.3
Iowa	9.8	4.9	4.3	<0.1	0.8
Kentucky	2.0	<1	0.5	0.1	1.0
Michigan	2.4	0.9	0.8	0.3	0.4
Minnesota	7.3	2.7	3.0	0.7	0.8
Missouri	5.2	1.1	2.0	0.4	1.7
Ohio	3.9	1.2	1.7	0.4	0.6
Pennsylvania	1.3	0.4	0.2	0.1	0.7
Tennessee	1.6	0.3	0.5	0.1	0.8
West Virginia	0.3	<0.1	<0.1	<0.1	0.2
Wisconsin	2.7	1.2	0.7	0.1	0.9

[a] USDA-NASS (2003).
[b] Botanical names corn (*Z. mays* L.), soybean (*G. max* L. Merr.), wheat (*Triticum* ssp.), hay, mixed legumes and grasses.

cropland in the central USA (Table 3). Iowa, Illinois, Minnesota and eastern Nebraska are the largest corn producers in the USA, while Iowa, Illinois, Minnesota and Indiana are the largest soybean producing states (JAWF, 2001). Some wheat is grown in the central USA, mostly in Minnesota. The largest area of hay in the region is found in Missouri. In Wisconsin, hay represents about one-third of the total cropland, which is used to support dairy production.

4. Croplands

4.1. Tillage practices

In corn/soybean cropping systems of the central USA, the moldboard plow has been the traditional, primary tillage tool (Allmaras and Dowdy, 1985). Primary conventional tillage (CT) on land planted to wheat mostly is chisel, disk or sweep plow (Allmaras et al., 1994). Tillage interaction with soil type and cropping system in the central USA has been extensively reviewed (Amemiya, 1977; Griffith et al., 1977; Allmaras et al., 1994; Lal et al., 1994a; Reeder, 2000).

Lal et al. (1994a) reported that about 45% of the land area in the central USA was in some form of conservation tillage (CST) that included no till (NT), ridge till, strip till and mulch till. The crop residue management report for the midwest region, which encompasses the majority of the central USA, indicates that 41% of the cropped land was in CST and another 24% in ‘‘reduced’’ till (CTIC, 2002). Therefore, 35% of the cropland is managed with <15% of residue coverage. The extent and form of CST utilized varies among states and cropping systems (Table 4). No till and mulch till are the dominant CST methods in the region. The cropland in NT ranges from a high of 54% in Tennessee to <3% in Minnesota and Pennsylvania. The fine-textured soils, cool-wet spring, and short growing season in Minnesota limit the adoption of this practice. The use of NT was most common with soybean, especially in double-cropped soybean systems. Advantages of ridge tillage include reduced labor costs, enhanced soil fertility, improved water management, improved water and wind erosion control, facilitated multiple cropping, enhanced rooting depth and improved pest management (Lal, 1990), however, only a small percentage of cropland in the central USA has been managed with ridge tillage (Table 4).

It should be noted that the categories provided by the Conservation Tillage Information Center do not specify the tillage or planting tool, rather the estimated surface cover is the criteria used for the various categories. There is also no indication of how long the tillage might have been used in a tillage rotation. A survey of tillage rotation in the central region by Hill (2001) reported that the average time in continuous NT was about 2.5 years in Illinois and Indiana, but only 1.4 years in Minnesota. Long-term conservation goals may not be achieved when conservation practices are interrupted and soil degradation occurs. Discussion of tillage effects on C cycling would be improved by including information on implement used, depth of tillage, duration of the particular tillage in a tillage rotation and residue burial patterns. Residue burial patterns are specific to the tillage tool (Allmaras et al., 1996).

Accelerated soil erosion contributes to losses in SOC and soil productivity and is a severe problem on a large portion of cropland in the central USA (USDA-NRCS, 2001). Soil erosion by water is more severe in more humid areas with high rainfall (e.g. Iowa) and wind erosion is more severe in semi-arid regions (e.g. western Minnesota) or areas with very sandy soil (e.g. central Wisconsin) of the central USA. Water and tillage erosion are more of a problem on sloping lands.

Table 4
Conservation tillage and cropping system in the central USA (adapted from Conservation Tillage Information Center for 2002)[a]

State		Percentage of cropland planted with tillage-planting system			
		No-till	Ridge-till	Mulch-till	Reduced-till[b]
Illinois		29	0	15	21
Indiana		39	<1	11	14
Iowa		23	1	33	29
Kentucky		51	0	17	12
Michigan		23	<1	8	19
Minnesota		3	1	20	31
Missouri		29	2	11	17
Ohio		41	<1	7	10
Pennsylvania		2	3	5	6
Tennessee		54	<1	8	13
West Virginia		38	0	6	10
Wisconsin		14	<1	19	15
Crop[c]	Percentage of cropland				
Corn (FS)[d]	46	17	<1	14	24
Soybean (FS)	44	36	<1	24	19
Soybean (DC)[e]	2	73	<1	12	6
Fall planted small grain	4	28	<1	16	20
Spring planted small grain	3	3	<1	14	27
Sorghum	<1	17	<1	14	19
Cotton	<1	33	16	2	7
Forage	2	13	NA[f]	11	17

[a] CTIC (2002).
[b] Retains 15–30% residue cover.
[c] Botanical names for crops corn (*Z. mays* L), soybean (*G. max* L. Merrill), small grain (e.g. Barley, *H. vulgare* L.; oat, *A. sativa* L.; wheat, *Triticum* ssp.; sorghum, *S. bicolor* L.), cotton (*Gossypium hirsutum* L.).
[d] Full season crop.
[e] Double crop.
[f] Not applicable.

Erosion hazards are caused by a combination of climate, highly erodible land, and intensive tillage. Lal (1995, 2003) and Lal et al. (1998) provided excellent reviews on SOC and erosion. Carbon loss and soil erosion are minimized with the use of continuous crop residue cover and CST. Conservation tillage during the growing season minimizes the disturbance of soil and plant root systems; root biomass may then contribute to SOC accumulation more effectively. Crop residue protects soil from wind and rain drop impact and provides C input (Mohamoud and Ewing, 1990; Savabi and Stott, 1994).

The initial impetus for CST was to increase surface residue for erosion control. Since organic rich surface horizons are transported preferentially by water and wind erosion, substantial C transport can occur (Cihacek et al., 1993; Fryrear, 1995; Lal, 2003). Soil loss of 11.2 Mg ha^{-1} $year^{-1}$ as sheet and rill erosion from a soil with 30 g C kg^{-1} in the surface horizon would represent a loss of 0.34 Mg C ha^{-1} $year^{-1}$. Much of this C may be repositioned on the landscape; however, deposition of eroded sediment in depression areas may lead to mineralization of C, which was previously protected within soil aggregates but now vulnerable to mineralization due to aggregate breakdown and more anaerobic conditions (Lal, 2003). The reported SOC sequestration benefit due to conversion from tilled to NT systems (e.g. Lal et al., 1994b; West and Post, 2002) is likely the result of both reduced erosion and reduced residue decomposition.

Tillage erosion, or tillage-induced translocation, which has often been confused with water erosion, is the net movement of soil down slope through the action of mechanical implements and gravity acting on loosened soil. Lindstrom et al. (1990, 1992), Govers et al. (1994, 1996), Lobb et al. (1995), Lobb and Kachanoski (1999) demonstrated that tillage erosion is a significant form of soil erosion and a major contributor to total soil erosion. Soil translocation from the moldboard plow and other tillage implements has been identified as a cause of soil movement from sensitive landscape positions resulting in unacceptable soil loss (Lindstrom et al., 1992; Govers et al., 1994; Lobb et al., 1995; Poesen et al., 1997). Soil is not directly lost from fields by tillage translocation; but it is moved away from convex slopes and deposited in concave positions. Lindstrom et al. (1992) showed that soil movement on a convex slope in Minnesota was approximately 30 Mg ha^{-1} year^{-1} from annual moldboard plowing. Tillage-induced translocation is a function of soil structure (Van Muysen et al., 1999), soil bulk density, moisture content (Montgomery et al., 1999), slope profile characteristics, slope contour (Lindstrom et al., 1990, 1992; Poesen et al., 1997), tillage speed and tillage depth (Lobb et al., 1995). The combination of these features is highly variable across the complex landscapes in the central USA. The combined effects of tillage and water erosion increase spatial variability of crop yield and reduce overall soil productivity (Schumacher et al., 1999; Reicosky et al., 2005).

4.2. Soil organic C: storage, management and carbon inputs

Soil organic C in tallgrass prairie soils, such as may be found in the western section of the central USA decreased to as much as 60% of the original concentration (Huggins et al., 1998a). Numerous studies have measured the decrease in residue mass and/or residue cover on the soil surface for various tillage and planting implements for row crops (Sloneker and Moldenhauer, 1977; Colvin et al., 1986; Johnson, 1988; Todd et al., 1988; Smith et al., 1990; Shelton et al., 1994, 1995; Wagner and Nelson, 1995; Hill and Stott, 2000) and small grains (Woodruff et al., 1965; Sloneker and Moldenhauer, 1977; Wagner and Nelson, 1995). Reversing this significant SOC loss with intensive agriculture would be beneficial to agriculture and society by gaining better control of the global C balance (Reicosky and Lindstrom, 1993; Reicosky, 1995; Reicosky et al., 2004). In Minnesota, enhanced CO_2 emission from tillage was found to be proportional to the volume of soil disturbed (Reicosky and Lindstrom, 1993; Reicosky, 1998). Conversion to CST in the moist conditions of the central USA may be especially important in increasing SOC and decreasing tillage-enhanced CO_2 emission, considering that <50% of cropland is currently under CST and <30% under NT in the region (Table 4).

Evidence in the literature indicates that intensive tillage decreases SOC. Results often support a recommendation to increase adoption of new and improved forms of CST or direct seeding to preserve or increase SOC (Reicosky et al., 1995; Paul et al., 1997; Lal et al., 1998). At the end of 12 years of continuous corn, Karlen et al. (1994) found NT and chisel-till systems accumulated a greater quantity of SOC in the 30 cm soil layer relative to the moldboard plow system. Carbon returned from aboveground net primary production was nearly the same for all three tillage systems. Similar results were found in other long-term tillage comparisons of continuous corn and a corn/soybean sequence in Ohio (Lal et al., 1994b; Dick and Durkalski, 1997; Dick et al., 1998; Huggins et al., 1998b). Wander et al. (1998) demonstrated that tillage impacted the depth distribution of SOC in three Illinois soils. Generally, NT increased SOC and particulate organic matter compared to CT (moldboard plow after corn and chisel plow after soybean) in the surface 5 cm, but decreased these concentrations in the 5–17.5 cm depth. These results demonstrated the importance of soil type and tillage tool interaction on SOC accumulation. The benefit of NT on SOC sequestration also varied with cropping system and depth of measurement (West and Post, 2002), which may explain apparent conflicts in the literature.

From baseline change between 1982 and 1997, SOC sequestration was estimated at 3.7 Tg C year^{-1} for the cool temperate moist and 11.9 Tg C year^{-1} for the warm temperate moist area in the USA, due to changes in tillage and other management factors (Sperow et al., 2003). West and Post (2002) reviewed SOC sequestration rates from many areas and systems. The rate of SOC storage due to conversion from CT to NT was highly variable, an average ± standard deviation of 44 treatment pairs from the central USA was 0.40 ± 0.61 Mg C ha^{-1} year^{-1} (Table 5). A mean SOC sequestration rate for the humid region in another analysis was estimated at 0.22 Mg C ha^{-1} year^{-1} (Six et al., 2004).

Table 5
Summary of soil organic C (SOC) storage in response to convention tillage (CT) and not tillage (NT) from studies in the central USA

Location	Crop/ fertilizer[a]	Duration (years)	Depth (cm)	Soil series[b]	Soil taxonomy	SOC-CT (Mg C ha^{-1})	SOC-NT (Mg C ha^{-1})	Citation
Nashua, IA	C	15	20	Floyd L, Kenyon L, Readlyn L	Aquic Hapludoll	60.3	71.1	Karlen et al. (1994)
DeKalb, IL	C–S	10.5	30	Drummer SiCL	Typic Haplaquoll	106.3	110.4	Wander et al. (1998)
Elwood, IL	C	6	30	Blount SiL	Aeric Ochraqualf	45.4	51.3	Mielke et al. (1986)
Monmouth, IL	C–S	10.5	30	Muscatine SiL	Aquic Hapludoll	72.5	78.6	Wander et al. (1998)
Perry, IL	C–S	10.5	30	Herrick SiL	Aquic Argiudoll	42.7	43.9	Wander et al. (1998)
Urbana, IL	C–S	8.5	30	Thorp SiL	Argiaquic Argialboll	54.7	59.4	Yang and Wander (1999)
West Lafayette, IN	C–S	11	20	Chalmers SiCL, Raub SiL	Typic Haplustoll, Aquic haploaquoll	60.0	73.0	Elliott et al. (1994)
West Lafayette, IN	C	11	20	Chalmers SiCL, Raub SiL	Typic Haplustoll, Aquic haploaquoll	77.0	65.0	Elliott et al. (1994)
Lexington, KY	C/168	5	30	Maury SiL	Typic Paleudalf	47.7	46.3	Blevins et al. (1977)
Lexington, KY	C/336	5	30	Maury SiL	Typic Paleudalf	45.9	52.8	Blevins et al. (1977)
Lexington, KY	C/0	5	30	Maury SiL	Typic Paleudalf	39.7	46.8	Blevins et al. (1977)
Lexington, KY	C/84	5	30	Maury SiL	Typic Paleudalf	47.8	48.4	Blevins et al. (1977)
Lexington, KY	C/84	20	30	Maury SiL	Typic Paleudalf	56.2	58.3	Ismail et al. (1994)
Lexington, KY	C/168	20	30	Maury SiL	Typic Paleudalf	56.4	58.6	Ismail et al. (1994)
Lexington, KY	C/336	20	30	Maury SiL	Typic Paleudalf	61.3	66.2	Ismail et al. (1994)
Lexington, KY	C/0	20	30	Maury SiL	Typic Paleudalf	48.9	55.3	Ismail et al. (1994)
Lexington, KY	C	11	30	Maury SiL	Typic Paleudalf	53.3	62.0	Mielke et al. (1986)
Lexington, KY	C (9 years) then C–S	25	20	Maury SiCL	Typic Paleudalf	31.3	37.4	Six et al. (2000)
Lexington, KY	C	22	20	Maury SiL	Typic Paleudalf	30.0	37.0	Elliott et al. (1994)
Lexington, KY	C/84 N	22	20	Maury SiL	Typic Paleudalf	34.0	40.0	Elliott et al. (1994)
Lexington, KY	C/164 N	22	20	Maury SiL	Typic Paleudalf	40.0	37.0	Elliott et al. (1994)
East Lansing, MI	C	7	20	Capac L	Aeric Ochraqualf	46.1	52.8	Pierce et al. (1994)
East Lansing, MI	C (9 years) then C–S	11	20	Capac L	Aeric Ochraqualf	38.2	42.9	Pierce et al. (1994)
Kellogg Biol Sta, MI	C–S–W	10	7.5	Not reported	Typic hapludalf	9.4	12.4	Robertson et al. (2000)
Kellogg Biol Sta, MI	C–S–W	10	20	Kalamazoo SL, Oshtemo SL	Typic Hapludalf	22.1	24.2	Six et al. (2000)

Table 5 (*Continued*)

Location	Crop/ fertilizer[a]	Duration (years)	Depth (cm)	Soil series[b]	Soil taxonomy	SOC-CT (Mg C ha^{-1})	SOC-NT (Mg C ha^{-1})	Citation
Rosemount, MN	C (stover removed)/0	13	30	Waukegan SiL	Typic Hapludoll	93.5	91.4	Clapp et al. (2000)
Rosemount, MN	C (stover removed)/200	13	30	Waukegan SiL	Typic Hapludoll	95.5	87.8	Clapp et al. (2000)
Rosemount, MN	C (stover retained)/200	13	30	Waukegan SiL	Typic Hapludoll	96.6	107.1	Clapp et al. (2000)
Rosemount, MN	C (stover retained)/0	13	30	Waukegan SiL	Typic Hapludoll	94.7	85.4	Clapp et al. (2000)
Waseca, MN	C	6	30	Webster CL	Typic Haplaquoll	106.9	106.8	Mielke et al. (1986)
Waseca, MN	C	11	15	Nicollet CL	Aquic Hapludoll	60.7	67.2	Mielke et al. (1986)
Columbia, MO	C	100	20	Mexico SiL, Lindley L	Udollic Ochraqualf, Typic Hapludalf	32.5	37.9	Buyanovsky and Wagner (1998)
Lincoln, NE	C (6 years) then C–S	12	30	Sharpsburg SiCL	Typic Argiudoll	52.1	57.3	Eghball et al. (1994)
Lincoln, NE	C	6	30	Crete-Butler SiCL	Pachic Argiustoll -Abruptic Argiaquoll	73.5	88.7	Mielke et al. (1986)
Coshocton, OH	C	34	15	Rayne SiL	Typic Hapludalf	25.6	57.6	Rhoton et al. (2002)
Waterman, OH	None	8	10	Crosby SiL	Aeric Ochraqualf	13.5	17.1	Duiker and Lal (1999)
Wooster, OH	C–S	30	30	Wooster SiL	Typic Fragiudalf	71.0	84.0	Dick et al. (1998)
Wooster, OH	C	30	30	Wooster SiL	Typic Fragiudalf	80	100	Dick et al. (1998)
Wooster, OH	C–O–M	30	30	Wooster SiL	Typic Fragiudalf	82	102	Dick et al. (1998)
Wooster, OH	C	29	15	Wooster SiL	Typic Fragiudalf	24.1	45.4	Lal et al. (1994b)
Wooster, OH	C–S	29	15	Wooster SiL	Typic Fragiudalf	38.9	27.0	Lal et al. (1994b)
Wooster, OH	C–O–M	29	15	Wooster SiL	Typic Fragiudalf	13.6	22.0	Lal et al. (1994b)
Wooster, OH	C	34	20	Wooster SiL	Typic Fragiudalf	33.8	38.1	Six et al. (2000)
Lancaster, WI	C	12	25	Rozetta -Palsgrove SiL	Typic Hapludalf	39.5	47.2	Karlen et al. (1994)
Mean ± standard deviation (paired *t*-test, $P < 0.001$, $n = 44$)						53.5 ± 25.2	59.1 ± 25.2	

[a] Crop abbreviations: A, alfalfa (*M. sativa* L); C, corn (*Z. mays* L.), hay; M, meadow; O, oats (*A. sativa* L.); S, soybean (*G. max* L. Merr.); W, wheat (*Triticum* ssp.)/values represent N application rate in kg ha^{-1} $year^{-1}$, when fertilizer was a treatment.
[b] Texture abbreviations: C, clay; L, loam; Sa, sand, Si, silt.

Converting from continuous corn to a rotation with three or more crops may increase SOC (Robinson et al., 1996; West and Post, 2002). But converting from continuous corn to corn–soybean rotation decreased SOC by 0.32 ± 0.99 Mg C ha^{-1} $year^{-1}$ (four treatment pairs; Table 6). Soybean residue appears to contribute little to SOC compared to corn (Layese et al., 2002). The soybean rhizosphere induces a

Table 6
Summary of soil organic C (SOC) storage in response to cropping system from studies in the central USA

Location	Tillage/ fertilizer[a]	Duration (years)	Depth (cm)	Soil series[b]	Soil taxonomy	TrtA[c]	SOC (Mg C ha^{-1})	TrtB	SOC (Mg C ha^{-1})	Citation
Wooster, OH	NT	19	30	Wooster SiL	Typic Fragiudalf	C–O–M[d]	45.4	C	22.0	Lal et al. (1994b)
Wooster, OH	CT	19	30	Wooster SiL	Typic Fragiudalf	C–O–M	17.7	C	24.5	Lal et al. (1994b)
Columbia, MO	CT	100	20	Mexico SiL Lindley L	Udollic Ochraqualf, Typic Hapludalf	C–W–C	36.0	W	35.9	Buyanovsky and Wagner (1998)
Columbia, MO	CT	100	20	Mexico SiL, Lindley L	Udollic Ochraqualf, Typic Hapludalf	C–W–C	32.5	C	35.9	Buyanovsky and Wagner (1998)
Kanawha, Nashua, Sutherland, IA	CT	36, 12, 34	15	Webster clay loam, Kenyon; Readlyn, Galva, silty clay loam	Typic Hapludoll; Aquic Hapludoll	C–C–O –M or C–O –M–M	48.9	C or C–S	42.0	Robinson et al. (1996)
West Lafayette, IN	NT	11	30	Chalmers SiCL, Raub SiL	Typic Haplustoll, Aquic Haploaquoll	C–S	65.0	C	73.0	Elliott et al. (1994)
West Lafayette, IN	CT	11	30	Chalmers SiCL, Raub SiL	Typic Haplustoll, Aquic Haploaquoll	C–S	77.0	C	60.0	Elliott et al. (1994)
Wooster, OH	NT	19	30	Wooster SiL	Typic Fragiudalf	C–S	45.4	C	27.0	Lal et al. (1994b)
Wooster, OH	CT	19	30	Wooster SiL	Typic Fragiudalf	C–S	17.7	C	22.7	Lal et al. (1994b)
Morris, MN	CT, 166 N	30	30	Hamerly CL, McIntosh SiL, Winger SiCL	Aeric, Aquic and Typic Calciaquolls	Grain	79.2	Silage	79.6	Wilts et al. (2004)
Morris, MN	CT, 87 N	30	30	Hamerly CL, McIntosh SiL, Winger SiCL	Aeric, Aquic and Typic Calciaquolls	Grain	81.4	Silage	76.2	Wilts et al. (2004)
Rosemount, MN	CT, 0 N	13	30	Waukegan SiL	Typic Hapludoll	Grain	93.5	Stover	94.7	Clapp et al. (2000)
Rosemount, MN	CT, 200 N	13	30	Waukegan SiL	Typic Hapludoll	Grain	95.5	Stover	96.6	Clapp et al. (2000)
Rosemount, MN	NT, 0 N	13	30	Waukegan SiL	Typic Hapludoll	Grain	91.4	Stover	85.4	Clapp et al. (2000)
Rosemount, MN	NT, 200 N	13	30	Waukegan SiL	Typic Hapludoll	Grain	87.8	Stover	107.1	Clapp et al. (2000)

[a] CT refers to conventional tillage and NT to no till. Values represent N application rate in kg ha^{-1} $year^{-1}$.
[b] Texture abbreviations: C, clay; L, loam; Sa, sand, Si, silt.
[c] TrtA treatment that was expected to sequester more organic C compared to TrtB.
[d] Crop abbreviations: A, alfalfa (*M. sativa* L); C, corn (*Z. mays* L.); Cl, clover (*Trifolium* sp.); G, grass; H, hay; M, meadow; O, oats (*A. sativa* L.); S, soybean (*G. max* L. Merr.); W, wheat (*Triticum* ssp.).

priming effect on soil organic matter, which has not been observed with other crops (Fu and Cheng, 2002; Cheng et al., 2003). In addition, soil erosion is often greater following soybean than corn (Moldenhauer and Wischmeier, 1969; Siemens and Oschwald, 1976, 1978; Oschwald and Siemens, 1976; Laflen and Moldenhauer, 1985). Currently, soybean is a major crop in the central USA (Table 3). Therefore, from an environmental standpoint, alternative management systems that diversify rotations and include cover crops could minimize C depletion and soil erosion during the soybean phase of the rotation.

In cropland, unharvested plant biomass provides C inputs, but unharvested crop residue values are not

Table 7
National average grain yield, harvest index and crop residue production for seven selected crops in 1940 and 2000 in the USA

Crop[a]	Grain yield ($Mg\ ha^{-1}$)[b]		Harvest index		Crop residue ($Mg\ ha^{-1}$)	
	1940[c]	2000[d]	1940[e]	2000[f]	1940	2000
Barley	1.3	3.9	0.3	0.5	3.5	3.9
Corn	1.9	8.4	0.4	0.5	3.5	7.5
Oat	1.2	2.2	0.2	0.4	3.9	2.8
Sorghum	0.9	4.0	0.3	0.5	1.8	4.5
Soybean	1.3	2.6	0.3	0.5	2.9	3.0
sunflower	NA[g]	1.4	NA	0.3	NA	2.8
Wheat	1.1	2.8	0.3	0.5	2.7	3.4

[a] Botanical names: Barley (*H. vulgare* L.), corn (*Z. mays* L), oat (*A. sativa* L.), sorghum, soybean (*G. max* L. Merrill), sunflower (*Helianthus annus* L), wheat (*Triticum* ssp.).
[b] Three-year average centered on the shown year.
[c] From Cochrane (1993).
[d] From USDA-NASS (2003).
[e] Allmaras et al. (1998).
[f] From Walker et al. (1998), Prince et al. (2001), Halvorson et al. (2002), Pedersen et al. (2004), Vetsch and Randall (2004) and Yang et al. (2004).
[g] Not available.

routinely reported. However, historical (Table 7) and most recent (Table 8) yield data are readily available through USDA-National Agricultural Statistic Service (USDA-NASS, 1997, 2003). Therefore the C input from crop residue input frequently must be estimated using a harvest index (HI) equation from Donald and Hamblin (1976):

$$HI = \frac{Y_{gr}}{Y_{biol}} \tag{1}$$

where Y_{gr} is the harvested grain (or other biomass) and Y_{biol} the total aboveground biomass that includes vegetative biomass plus harvested grain. Vegetative biomass (Y_r) is then estimated from harvested grain biomass:

$$Y_r = Y_{gr}\left[\frac{1}{HI} - 1\right] \tag{2}$$

The HI of six common crops in the central USA has increased about 45% from 1940 to 1990 (Allmaras et al., 1998) due to genetic improvement with little additional increase since 1990. Aboveground biomass increased dramatically for corn (112%) and sorghum (*Sorghum bicolor* L. Moench) (148%), modestly for wheat (27%) and barley (*H. vulgare* L.) (12%), remained nearly constant for soybean (2%) and decreased for oat (*A. sativa* L.) (−27%) between 1940 and 2000 (Table 7). Lynch and Frey (1993) reported 8% lower residue production by five oat cultivars released prior to 1963 compared to five cultivars released during 1970–1987. Much of the observed yield improvement has been due to higher HI, meaning crop residue and C inputs have not kept pace with increased grain yield.

It is proposed that increased crop biomass inputs together with changes in soil management (e.g. CST or NT) will result in soils acting as net C sinks rather than net C sources. Tollenaar and Lee (2002) estimated the potential yield for corn at 25 $Mg\ ha^{-1}$. Duvick (1992) and Duvick et al. (2004) found no limit to corn yield from improved hybrids during 1930–2000 in the central USA. Current corn and wheat yields through-

Table 8
State average yield in 2003 for major crops in states from the central USA[a]

State	Corn	Soybean ($Mg\ ha^{-1}$)	Wheat ($Mg\ ha^{-1}$)	Hay
Illinois	11.1	2.6	4.7	7.9
Indiana	9.9	2.8	5.0	7.3
Iowa	10.6	2.3	4.4	7.7
Kentucky	9.2	3.1	4.5	5.8
Michigan	8.5	2.0	4.9	6.7
Minnesota	9.9	2.3	4.2	5.6
Missouri	7.3	2.1	4.4	4.3
Ohio	10.6	2.8	4.9	6.6
Pennsylvania	7.8	3.0	3.1	5.5
Tennessee	8.9	3.0	3.6	5.2
West Virginia	7.8	3.0	2.9	4.4
Wisconsin	8.7	2.0	5.0	4.7
National average	9.6	2.4	3.2	7.3

[a] USDA-NASS (2003).

out much of the central USA are above the national average (Tables 7 and 8). Amount of C in aboveground residue of corn assuming a grain yield of 20 Mg ha^{-1}, a HI of 0.56 and a C content of 0.40 would return 6.3 Mg C ha^{-1} to the field. In a recent review of literature mostly from tilled systems, Wilhelm et al. (2004) reported that it takes ~2.2 Mg C ha^{-1} (5.4 Mg aboveground residue input ha^{-1}) to maintain SOC. The contribution of root-derived C was not included in this estimate. Root-derived C could contribute 1.4 (Bolinder et al., 1999) to 3-fold (Allmaras et al., 2004) of the C retained in SOC compared with aboveground C input. Allmaras et al. (2004) reported that the contribution of root-derived C to SOC increased 36–55% with than without N fertilization, due to increased rhizodeposition. Current and projected C inputs from corn production should be sufficient to maintain and/or increase SOC; however, empirical data are needed to test this hypothesis.

Residue placement, element size and orientation have significant effects on decomposition. Incorporation of residue tends to increase rate of decomposition. For example, Ghidey and Alberts (1993) found annual mass loss of 41, 66 and 78% for above-surface, surface and buried corn residue and 37, 66 and 79%, respectively, for soybean residue. Gale and Cambardella (2000) reported that only 16% of surface oat residue C was found in the soil during a 360-day laboratory experiment while 42% of the oat root-derived C remained in the soil.

Residue/soil combinations consistently show a pattern of increasing residue decomposition rate as soil water potential increases until aeration becomes limiting (Stott et al., 1986; Schomberg et al., 1994) and as temperature increases (Waksman and Gerretsen, 1931; Stott et al., 1986). Cool, moist conditions created by the presence of a layer of surface residue in NT systems, likely will slow the decomposition of not only surface residue but also of decaying roots (Stott et al., 1986). High biomass production and slow decomposition of crop residue in dominant cropping systems in the region probably account for the high C storage potential (Sperow et al., 2003). However, the same cool, wet conditions in the northern part of the central USA would also delay crop germination and emergence. These factors have contributed to slow adoption of NT in Minnesota.

4.3. Cover crops

Cover crops are grown in addition to a primary cash crop, functioning for erosion control and organic N enrichment (Allmaras et al., 1994). Cover cropping has been most successful below 40°N and with >500 mm annual precipitation (Allmaras et al., 1994). Ismail et al. (1994) evaluated the long-term effect of tillage in continuous corn with a rye (*Secale cereale* L.) cover crop in Kentucky. Soil organic C in the top 30 cm did not change from 1975 to 1980, but substantially increased from 1980 to 1989. Potential long-term impact of cover crops on SOC was illustrated by Lee et al. (1993) using the EPIC model on a typical "Corn Belt soil" from the central USA. A 2-fold increase in SOC was primarily related to input associated with a cover crop, suggesting that long-term cover crops could help offset SOC loss due to intensive tillage and maintain soil quality. Research is in progress to evaluate the use of fall-planted rye cover crop in various cropping systems across Minnesota (Porter, 2004). Adaptation and selection of cover crop species to the central USA provides an opportunity to improve cover crop management especially in the northern areas of this region (Allmaras et al., 1994).

4.4. Manure additions

Much of the grain produced in the central USA is used to feed beef, dairy, swine and poultry. A natural asset of combined crop–livestock agricultural systems is C and nutrient-rich manure. Manure application in modern cropping systems is known to sustain or increase SOC (Vitosh et al., 1973; Tester, 1990; Eghball, 2002; Edmeades, 2003). Manures are also considered valuable for their nutrient content (especially N and P) and contribution to soil quality. Manure addition can also improve soil physical properties such as available water holding capacity (Hudson, 1994; Rawls et al., 2003). Manure addition may not be entirely beneficial as increased production of CH_4 and N_2O emission can occur (Cates and Keeney, 1987; Paul et al., 1993; Coyne et al., 1995; Chang et al., 1998). Although manure application may lead to increased N_2O emission, this may occur with high N fertility regardless of N source. Improved management of animal manures, such as avoiding excess application and optimizing the timing of application to synchronize with crop uptake, will ensure the most positive effects of manure additions on SOC storage and GHG emission.

4.5. N_2O emission

Generation of N_2O in soil occurs from nitrification and denitrification, two major microbial pathways of soil N transformation, as well as from the chemical process of chemodenitrification (Conrad, 1995; Venterea and Rolston, 2000). Generally, denitrification is considered to be the most important N_2O source in agricultural soils. Due to its high proportion of agricultural land, the central USA is estimated to contribute more than half of all agriculture-derived N_2O emission in the USA. Model estimates by Mummey et al. (1998) suggest that N_2O emission from agriculture in the north central (MN, WI, IA, MI, MO, IL, IN, and OH) and south central (OK, TX, AR, MS, LA, KY, TE, AL) regions combined contribute 62–65% of total N_2O emission from agriculture in the USA, with the north central states contributing the greater share (~34%). Li et al. (1996) estimated the same north central region might contribute 25–27%, of total agriculture-derived N_2O emission in the USA. Therefore, adoption of improved agricultural management systems in the central USA could greatly reduce total GHG emission.

Li et al. (1996) modeled effects of CT (twice yearly tillage to a depth of 15–25 cm), CST (chisel plow occurring 15 days prior to planting once a year, either in spring or fall) and NT on simulated N_2O emission. Fall CST and NT both resulted in approximately a 40% reduction in N_2O emission compared to spring CST and CT in simulated Iowa corn fields. Reduced rate of N mineralization, higher water-holding capacity and diminished frequency of wet–dry cycles under reduced tillage intensity were considered reasons for the large reduction in N_2O emission. Mummey et al. (1998) found that simulated N_2O emission in the north central region was 7.5% higher under NT than under CT. In contrast to the results of Li et al. (1996), Mummey et al. (1998) concluded that increased soil moisture associated with NT took precedence over increased decomposition with CT.

Several studies in the central USA have documented the effects of reduced tillage on soil properties (bulk density, water content, aeration, aggregate stability, size and interconnection of macropores, surface crusting) that may influence N_2O emission (Triplett et al., 1968; Mannering et al., 1975; Griffith et al., 1977, 1986; Gantzer and Blake, 1978; Dick, 1983; Betz et al., 1998; Venterea et al., 2005). Increased bulk density, increased water content and reduced O_2 increase N_2O emission. Improved aggregate stability, improved drainage and reduced surface crusting decrease N_2O emission. Since these properties are not independent of each other, it is difficult to predict the effects of reduced tillage (with respect to intensity or depth) and residue management on N_2O emission.

There are few direct studies of tillage management on N_2O emission in the region. Reduced tillage increases surface residue, which can result in wetter soil conditions (Sauer et al., 1996). Wetter soil conditions due to surface residue have been implicated for causing increased production of CH_4 and N_2O (Aulakh et al., 1984; Goodroad et al., 1984; Lal et al., 1995; Paustian et al., 1995). Linn and Doran (1984) reported 3.4 and 9.4 times greater CO_2 and N_2O production from surface NT soils as compared to plowed soils at sites in Illinois, Kentucky, Minnesota and Nebraska. Chan and Parkin (2001) measured CH_4 emission from several natural and managed ecosystems in Iowa. They found more systems that were a net sink for CH_4, during a year with above-normal precipitation. A NT soybean field had net CH_4 emission in a low (more moist) area and net uptake in an adjacent well-drained area.

Lower soil temperature early in the growing season under reduced tillage may result in lower rate of N mineralization from organic matter (Griffith et al., 1977; Fox and Bandel, 1986), thereby limiting NO_3^- accumulation necessary for denitrification. Spring tillage may cause a transient burst in microbial activity that controls N mineralization, resulting in increased NO_3^- accumulation (Jackson et al., 2003). Thus, soil under CT could exhibit higher denitrification in spring if N fertilizer were applied, especially in the form of NO_3^-, or if significant residual soil NO_3^- remained.

Goodroad et al. (1984) reported growing season N_2O emission in reduced tillage corn ranging from 3.5 to 6.3 kg N ha^{-1}, which was higher than from tilled plots in Wisconsin. Jacinthe and Dick (1997) measured N_2O emission in a rotation study and found N_2O emission from corn and soybean under chisel tillage was greater than under NT (corn) or reduced tillage (corn and soybean) in Ohio. In both these studies, tillage was confounded with fertilizer N addition and cropping sequence, making conclusions about specific management effects difficult.

Robertson et al. (2000) conducted a whole-system GHG budget for cropping systems in Michigan under: (1) CT and NT systems receiving equivalent inputs of chemical fertilizers, (2) a CT system receiving reduced chemical inputs and a leguminous cover crop and (3) an organically managed system with a leguminous cover crop. Except for the accumulation of SOC that occurred under NT, N_2O emission represented the single greatest component of the total GHG budget in all systems. Soil N_2O emission under NT was 7.7% higher than under CT. Increased N_2O emission with NT represented a small offset (3.6%) of the SOC gain that occurred during 10 years of NT. Significant but transient increases in N_2O emission and total GHGs were observed under NT compared with moldboard plow within 3 weeks following fertilizer application in a corn–soybean rotation in Minnesota (Venterea, unpublished data). Additional long-term studies similar to Robertson et al. (2000) but in additional locations, are needed. This is especially true given the recent evaluation of Six et al. (2004) suggesting that N_2O emission under reduced tillage will vary both with climatic regime and time on the scale of years to decades.

It is possible that management resulting in SOC sequestration could do so at the expense of increased N_2O emission. For any given SOC accumulation rate resulting from reduced tillage, an increase in N_2O emission that would counterbalance this gain from a GHG standpoint, can be calculated from differences in GWP between N_2O and CO_2 on a molecular basis. For example, an increase in N_2O emission of 2.1 kg N_2O-N ha^{-1} $year^{-1}$ would completely offset the sequestration of 0.30 Mg C ha^{-1} $year^{-1}$. The offsetting effect of increased N_2O emission across different fertilizer management and cropping systems can be estimated with an IPCC emission factor that predicts N_2O emission as a function of N input (Fig. 1). Current IPCC calculation of N_2O emission from cropped non-Histosols assumes a background flux of 1 kg N ha^{-1} $year^{-1}$ plus a flux of $1.25 \pm 1\%$ of all unvolatilized N inputs in the form of synthetic and organic fertilizers, crop residues and biological fixation (IPCC, 1997). Thus, for a NT cropping system that received 100 kg N ha^{-1} $year^{-1}$ (net from all sources), the estimated annual N_2O emission of 2.25 kg N ha^{-1} $year^{-1}$ would have to increase by 32–97% to completely offset C gains of 0.10–0.30 Mg C ha^{-1} $year^{-1}$.

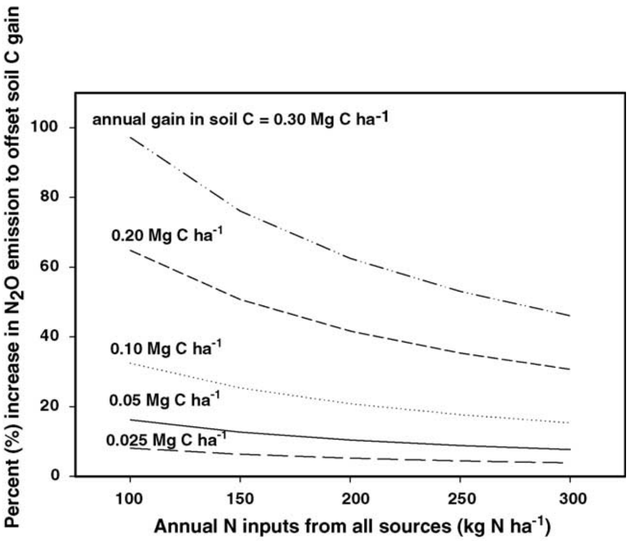

Fig. 1. The percent increase in N_2O emission resulting in a complete GHG offset of soil C gain as a function of both total annual N inputs and annual rate of soil C sequestration. Emission of N_2O is estimated as a function of N inputs using current IPCC emission factors (IPCC, 1997).

5. Soil organic C sequestration and trace gas emission in pastures

Information concerning SOC sequestration under managed grasslands, both grazed and mechanically harvested is limited (Schnabel et al., 2001) with almost no data specific to the central USA. Soil organic C sequestration potential in pastures can be affected by management intensity, fertilizer and lime inputs, grazing frequency and stocking rates or mowing frequency, plant species composition and animal type. In general, SOC increases with improved management of fertilizer, grazing and species selection (Conant et al., 2001). Follett et al. (2001) estimated that improving pastures through fertilization, liming, and species selection together with grazing management could increase SOC sequestration by 10–34 Tg C year^{-1} across the USA. Accurately determining SOC sequestration in pastures in the central USA will face the same spatial variability issues observed in other regions that can result when disproportionate amounts of dung and urine are deposited (West et al., 1989; Franzluebbers et al., 2000).

As summarized by Schnabel et al. (2001), soil management factors that improve plant productivity might also increase SOC, but there are limits and exceptions. For example, liming and the elimination of P deficiency increased SOC (Ridley et al., 1990; Haynes and Williams, 1992). The carbon cycling in grasslands (CCGRASS) model predicts that low to moderate N applications (100–250 kg N ha^{-1} year^{-1}) would lead to the greatest increase in SOC (Van den Pol-van Dasselaar and Lantinga, 1995), but larger N addition, lower C:N ratio of plant materials and increasing N availability to microbes could increase organic matter decomposition (Schnabel et al., 2001). Warm- and cool-season grasses also respond differently to N fertilization. Warm-season grasses produce greater biomass and subsequent organic C returned to the soil than cool-season grasses without N or with moderate N fertilization, but little difference occurs between the two with high fertility (Stout, 1992; Stout and Jung, 1992, 1995; Wedin and Tilman, 1996). Adding legumes to grasslands can increase N availability and plant biomass production, but SOC accumulation may be smaller than expected due to production of low C:N organic matter, which is readily mineralized (Schnabel et al., 2001).

Despite improved management, the additional quantity of SOC sequestered in pasture soils is expected to be much less than the quantity that can be stored by altering the management of cultivated soils. Schnabel et al. (2001) concluded that SOC in established, managed pastures is likely near saturation and that additional SOC sequestration may be limited. Nevertheless, pastures and grassland provide a large C sink that should not be overlooked. Policies and programs that encourage the conservation of current grasslands and conversion of marginally productive croplands to perennial vegetation [e.g., conservation reserve program (CRP) in the USA] should be viewed as critical strategies to combat global climate change. From the few studies available in the region, CRP increased SOC sequestration by 4.2 ± 4.5 Mg C ha^{-1} year^{-1} (Table 9).

Little information is available concerning N_2O emission and CH_4 flux from pastures and hay fields in the central USA. General principles and challenges observed in pastures in other regions and countries can be expected to apply. For example, N_2O emission will likely increase following the application of mineral

Table 9
Summary of soil organic C (SOC) storage in cropland and adjacent grassland with enrollment in the conservation reserve program in the central USA

Location	Duration (years)	Sampling depth (cm)	SOC in cropland (Mg ha^{-1})	SOC in CRP (Mg ha^{-1})	Citation
Butler County, IA	7–8	20	42	44	Huggins et al. (1997)
Henry County, IA	7–8	20	32	44	Huggins et al. (1997)
MN	7–8	20	50	54	Huggins et al. (1997)
Lamberton, MN	6	7.5	64	65	Huggins et al. (1997)
Dane County, WI	8	10	30	32	Kucharik et al. (2003)

fertilizer or manure as observed in European grasslands and other regions (Chadwick et al., 2000; Clayton et al., 1997; Glatzel and Stahr, 2001; Kammann et al., 1998; Ryden, 1981; Velthof and Oenema, 1995). Manure application to pasture does not appear to significantly impact CH_4 emission (Chadwick et al., 2000). Dung and urine deposition can be expected to generate "hot spots" of N_2O emission (Allen et al., 1996; Flessa et al., 1996; Williams et al., 1999), which would complicate accurate N_2O emission determination from pastures, especially when small chambers are used. The use of micro-meteorological methods to measure N_2O emission in pastures would integrate spatial variability.

Most soils in the central USA are exposed to freezing and thawing events. Substantial N_2O emission from grasslands in other location has been reported in response to soil freezing and thawing (Velthof et al., 1996; Kammann et al., 1998; Williams et al., 1999). Emission associated with freezing and thawing appear to occur as a result of accumulation of organic N in frozen soil, followed by N mineralization as the soil thaws, and finally nitrification and subsequent denitrification leading to N_2O production during the post-thaw period (Müller et al., 2002). As research in the central USA proceeds to quantify GHG emission, it will be important to include sampling of freeze–thaw events.

Dairy forage production is an important component of agriculture in portions of the central USA, but SOC sequestration potential and GHG emission, have not been reported for these systems. Silage corn and alfalfa (*Medicago sativa* L.) rotations are commonly grown by confinement dairy operations. The nearly complete removal of aboveground plant biomass by reduces C inputs and could reduce SOC sequestration compared to grain production systems; however, return of manure to soils could be balancing C removal in forage. Removal of stover or silage harvest without manure return reduced SOC under continuous corn (Table 6).

6. Research needs in the central USA

There is a need for integration of physical, chemical and biological features from ecoregions, MLRA soils information, and climate zones with tillage and cropping systems, to better predict SOC storage and cycling, GHG emission (CO_2, CH_4 and N_2O) and offsets in agricultural production systems. This literature review identified knowledge gaps in the potential of reduced tillage and NT to increase C storage and affect N_2O emission, particularly how tillage systems interact with cropping systems. Intensive tillage has been one of the main causes for SOC loss via increased erosion and C mineralization. Plant residue quantity (above and belowground) and quality are the largest determinants of SOC input. Information is needed on total biomass produced, as well as on labile forms of C that pass through the plant and are exuded from roots, which contribute to SOC cycling and sequestration. Research is needed to bring together all aspects of tillage, fertility, crop systems management as well as crop residue and manure management into a comprehensive analysis of GHG emission. Studies on SOC management need to provide clear descriptions of all tillage and seeding equipment used, depth, speed and extent of soil disturbance, residue mixing, tillage rotation and frequency and crop rotation. Cover crop species and management strategies for utilizing cover crops need to be enhanced in the central USA. Additional information is needed on an acceptable amount of residue that can be removed for alternate uses (e.g. bio-fuels) before soil properties are degraded. Depth distribution of SOC sequestration needs to be clarified with C measurements that extend below the maximum depth of tillage under different cropping systems. Much of the limited data on GHG emission from cropland or managed pastures for the central USA was determined from small flux chambers without assessment of spatial variability. Utilization of large-area trace-gas flux measurements is needed to accurately quantify the impact of management decisions on GHG emission at the field scale. The interaction of tillage and fertilization (methods, carriers and frequency) on SOC sequestration and GHG emission needs to be determined across the region in all agro eco-systems. Research is needed to quantify the contribution of SOC management to enhance environmental benefits and social and economic impacts associated with a secure and sustainable food production system. Addressing these issues will provide new knowledge for enhancing global SOC management, leading to a sustainable agriculture that protects environmental quality.

Acknowledgements

The authors would like to thank B. Burmeister for her careful proof reading and assistance.

References

Allen, A.G., Jarvis, S.C., Headon, D.M., 1996. Nitrous oxide emission from soils due to inputs of nitrogen from excreta returned by livestock on grazed grassland in the U.K. Soil Biol. Biochem. 28, 597–607.

Allmaras, R.R., Copeland, S.M., Copeland, P.J., Oussible, M., 1996. Spatial relations between oat residue and ceramic spheres when incorporated sequentially by tillage. Soil Sci. Soc. Am. J. 60, 1209–1216.

Allmaras, R.R., Dowdy, R.H., 1985. Conservation tillage systems and their adoption in the United States. Soil Till. Res. 5, 197–222.

Allmaras, R.R., Langdale, G.W., Unger, T.W., Dowdy, R.H., 1991. Adoption of conservation tillage and associated planting systems. In: Lal, R., Pierce, F.J. (Eds.), Soil Management for Sustainability. Soil Water Conserv. Soc., Ankeny, IA, pp. 53–83.

Allmaras, R.R., Linden, D.R., Clapp, C.E., 2004. Corn–residue transformations into root and soil carbon as related to nitrogen, tillage, and stover management. Soil Sci. Soc. Am. J. 68, 1366–1375.

Allmaras, R.R., Power, J.F., Tanaka, D.L., Copeland, S.M., 1994. Conservation tillage systems in the northern most central United States. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, Boca Raton, FL, pp. 255–284.

Allmaras, R.R., Wilkins, D.W., Burnside, O.C., Mulla, D.J., 1998. Agricultural technology and adoption of conservation practices. In: Pierce, F.J., Frye, W.W. (Eds.), Advanced Soil Water Conservation. Sleeping Bear Press, Chelsea, MI, pp. 99–158.

Amemiya, M., 1977. Conservation tillage in the western corn belt. J. Soil Water Conserv. 32, 29–36.

Aulakh, M.S., Rennie, D.A., Paul, E.A., 1984. Gaseous nitrogen losses from soils under zero-till as compared with conventional-till management systems. J. Environ. Qual. 13, 130–136.

Bailey, R.G., 1995. Description of the Eco-regions of the United States. Misc. Publ. 1391, 2nd ed. United States Department of Agriculture-Forest Service, 108 pp.

Betz, C.L., Allmaras, R.R., Copeland, S.M., Randall, G.W., 1998. Least limiting water range: traffic and long-term tillage influence in a Webster soil. Soil Sci. Soc. Am. J. 62, 1384–1393.

Blevins, R.L., Thomas, G.W., Cornelius, P.L., 1977. Influence of no-tillage and nitrogen fertilization on certain soil properties after 5 years of continuous corn. Agron. J. 69, 383–386.

Bolinder, M.A., Angers, D.A., Giroux, M., Laverdiere, M.R., 1999. Estimating C inputs retained as soil organic matter from corn (*Zea mays* L.). Plant Soil 215, 85–91.

Buyanovsky, G.A., Wagner, G.H., 1998. Carbon cycling in cultivated land and its global significance. Glob. Change Biol. 4, 131–141.

Cates Jr., R.L., Keeney, D.R., 1987. Nitrous oxide production throughout the year from fertilized and manured maize fields. J. Environ. Qual. 16, 443–447.

Chadwick, D.R., Pain, B.F., Brookeman, S.K.E., 2000. Nitrous oxide and methane emissions following application of animal manures to grassland. J. Environ. Qual. 29, 277–287.

Chan, A.S.K., Parkin, T.B., 2001. Effect of land use on methane flux from soil. J. Environ. Qual. 30, 786–797.

Chang, C., Cho, C.M., Janzen, H.H., 1998. Nitrous oxide emission from long-term manured soils. Soil Sci. Soc. Am. J. 62, 677–682.

Cheng, W., Johnson, D.W., Fu, S., 2003. Rhizosphere effects on decomposition: control of plant species, phenology and fertilization. Soil Sci. Soc. Am. J. 67, 1418–1427.

Cihacek, L.J., Sweeney, M.D., Deibert, E.J., 1993. Characterization of wind erosion sediments in the Red River Valley of North Dakota. J. Environ. Qual. 22, 305–310.

Clapp, C.E., Allmaras, R.R., Layese, M.F., Linden, D.R., Dowdy, R.H., 2000. Soil organic carbon and 13C abundance as related to tillage, crop residue, and nitrogen fertilization under continuous corn management in Minnesota. Soil Till. Res. 55, 127–142.

Clayton, H., McTaggart, I.P., Parker, J., Swan, L., Smith, K.A., 1997. Nitrous oxide emissions from fertilised grassland: a 2-yearstudy of the effects of N fertiliser form and environmental conditions. Biol. Fert. Soils 25, 252–260.

Cochrane, W., 1993. The Development of American Agriculture: A Historical Analysis, 2nd ed. University of Minnesota Press, Minneapolis, MN.

Colvin, T.S., Berry, E.C., Erbach, D.C., Laflen, J.M., 1986. Tillage implement effects on corn and soybean residue. Trans. ASAE 29, 56–59.

Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland management and conversion into grassland: Effects on soil carbon. Ecol. Appl. 11, 343–355.

Conrad, R., 1995. Soil microbial processes involved in production and consumption of atmospheric trace gases. In: Jones, J. (Ed.), Adv. Microb. Ecol. Plenum Press, New York, pp. 207–250.

Coyne, M.S., Villalba, A., Blevins, R.L., 1995. Nitrous oxide loss from poultry manure-amended soil after rain. J. Environ. Qual. 24, 1091–1096.

CTIC, 2002. National Crop Residue Management Survey. Conservation Tillage Data. Conservation Technology Information Center (posted 2002; verified July 13, 2004). http://www.ctic.purdue.edu/CTIC/CRM.html.

Dick, W.A., 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J. 47, 102–107.

Dick, W.A., Blevins, R.L., Frye, W.W., Peters, S.E., Christenson, D.R., Pierce, F.J., Vitosh, M.L., 1998. Impacts of agricultural management practices on C sequestration in forest-derived soils of the eastern Corn Belt. Soil Till. Res. 47 (3/4), 235–244.

Dick, W.A., Durkalski, J.T., 1997. No-till production agriculture and carbon sequestration in a typic Fragiudalf soil of northeastern Ohio. In: Lal, R., Kimball, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 59–71.

Donald, C.M., Hamblin, J., 1976. The biological yield and harvest index of cereals as an agronomic and plant breeding criteria. Adv. Agron. 28, 361–405.

Duiker, S.W., Lal, R., 1999. Crop residue and tillage effects on carbon sequestration in a Luvisol in central Ohio. Soil Till. Res. 52, 73–81.

Duvick, D.N., 1992. Genetic contributions to advances in yield of U.S. maize. Maydica 37, 69–79.

Duvick, D.N., Smith, J.S.C., Cooper, M., 2004. Changes in performance parentage, and genetic diversity of successful corn hybrids, 1930–2000. In: Smith, C.W., Betrán, J., Runge, E.C.A. (Eds.), Corn, Origin, History, Technology, and Production. Wiley, Mississauga, Ont., Canada, pp. 65–98.

Edmeades, D.C., 2003. The long-term effects of manures and fertilizers on soil productivity and quality: a review. Nutr. Cycl. Agroecosyst. 66, 165–180.

Eghball, B., Mielke, L.N., McCallister, D.L., Doran, J.W., 1994. Distribution of organic carbon and inorganic nitrogen in a soil under various tillage and crop sequences. J. Soil Water Conserv. 49, 201–205.

Eghball, B., 2002. Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. Agron. J. 94, 128–135.

Elliott, E.T., Burke, I.C., Monz, C.A., Frey, S.D., Lyon, D.J., Paustian, K., Collins, H.P., Halvorson, A.D., Huggins, D.R., Paul, E.A., Turco, R.F., Cole, C.V., Hickman, M.V., Blevins, R.L., Frye, W.W., 1994. Terrestrial carbon pools: preliminary data from Corn Belt and Great Plains regions. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. SSSA Special Publication No. 35. Soil Sci. Soc. Am., Agron. Soc. Am., Madison, WI, pp. 179–191.

Eve, M.D., Paustian, K., Follett, R.F., Ellliot, E.T., 2001. A national inventory of changes in soil carbon from national resources inventory data. In: Lal, R., Kimball, J.M., Follett, R.F., Stewart, B.A. (Eds.), Assessment Methods for Soil Carbon. Lewis Publishers, Boca Raton, FL, pp. 593–610.

Flessa, H., Dörsch, P., Beese, F., König, H., Bouwman, A.F., 1996. Influence of cattle wastes on nitrous oxide and methane fluxes in pasture lands. J. Environ. Qual. 25, 1366–1370.

Follett, R.F., Kimble, J.M., Lal, R. (Eds.), 2001. The potential of U.S. grazing lands to sequester soil carbon. In: The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publishers, Boca Raton, FL, p. 512.

Fox, R., Bandel, V., 1986. Nitrogen utilization with no-tillage. In: Sprague, M., Triplett, G. (Eds.), No-tillage and Surface Tillage Agriculture. Wiley, New York, pp. 117–148.

Franzluebbers, A.J., Follett, R.F., 2005. Greenhouse gas contributions and mitigation potential in agricultural regions of North America: introduction. Soil Till. Res., this issue.

Franzluebbers, A.J., Stuedeman, J.A., Schomberg, H.H., 2000. Spatial distribution of soil carbon and nitrogen pools under grazed tall fescue. Soil Sci. Soc. Am. J. 64, 635–639.

Fryrear, D.W., 1995. Soil losses by wind erosion. Soil Sci. Soc. Am. J. 59, 668–672.

Fu, S., Cheng, W., 2002. Rhizosphere priming effects on the decomposition of soil organic matter in C4 and C3 grassland soils. Plant Soil 283, 289–294.

Gale, W.J., Cambardella, C.A., 2000. Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. Soil Sci. Soc. Am. J. 64, 190–195.

Gantzer, C., Blake, G., 1978. Physical characteristics of Le Sueur clay loam soil following no-till and conventional tillage. Agron. J. 70, 853–857.

Ghidey, F., Alberts, E.E., 1993. Residue type and placement effects on decomposition: field study and model evaluation. Trans. ASAE 36, 1611–1617.

Glatzel, S., Stahr, K., 2001. Methane and nitrous oxide exchange in differently fertilized grassland in southern Germany. Plant Soil 231, 21–35.

Goodroad, L.L., Keeney, D.R., Peterson, L.A., 1984. Nitrous oxide emissions from agricultural soils in Wisconsin. J. Environ. Qual. 13, 557–561.

Govers, G., Quine, T.A., Desmet, P.J.J., Walling, D.E., 1996. The relative contribution of soil tillage and overland flow erosion to soil redistribution on agricultural land. Earth Surf. Processes 21, 929–946.

Govers, G., Vandaele, K., Desmet, P.J.J., Poesen, B.K., 1994. The role of tillage in soil redistribution on hillslopes. Eur. J. Soil Sci. 45, 469–478.

Griffith, D., Mannering, J., Box, J., 1986. Soil and moisture management with reduced tillage. In: Sprague, M., Triplett, G. (Eds.), No-tillage and Surface Tillage Agriculture. Wiley, New York, pp. 19–57.

Griffith, D.R., Mannering, J.V., Moldenhauer, W.C., 1977. Conservation tillage in the eastern Corn Belt. J. Soil Water Conserv. 32, 20–28.

Halvorson, A.D., Peterson, G.A., Reule, C.A., 2002. Tillage system and crop rotation effects on dryland crop yields and soil carbon in the central Great Plains. Agron. J. 94, 1429–1436.

Haynes, R.J., Williams, P.H., 1992. Accumulations of soil organic matter and the forms, mineralization potential and plant-availability of accumulated organic sulfur: Effects of pasture improvement and intensive cultivation. Soil Biol. Biochem. 24, 209–217.

Hill, P.R., 2001. Use of continuous no-till and rotational tillage systems in the central and northern corn belt. J. Soil Water Conserv. 56, 286–290.

Hill, P.R., Stott, D.E., 2000. Corn residue retention by a combination chisel plow. Soil Sci. Soc. Am. J. 64, 293–299.

Hudson, B.D., 1994. Soil organic matter and available water capacity. J. Soil Water Conserv. 49, 189–194.

Huggins, D.R., Allan, D.L., Gardner, J.C., Karlen, D.L., Bezdicek, D.F., Rosek, M.J., Almas, M.J., Flock, M., Miller, B.S., Staben, M.L., 1997. Enhancing carbon sequestration in CRP-managed land. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A.

(Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, USA, pp. 323–334.

Huggins, D.R., Buyanovsky, G.A., Wagner, G.H., Brown, J.R., Darmody, R.G., Peck, T.R., Lesoing, G.W., Vanotti, M.B., Bundy, L.G., 1998a. Soil organic C in the tallgrass prairie-derived region of the Corn Belt: Effects of long-term crop management. Soil Till. Res. 47 (3/4), 219–234.

Huggins, D.R., Clapp, C.E., Allmaras, R.R., Lamb, J.A., Layese, M.F., 1998b. Carbon dynamics in corn–soybean sequences as estimated from natural carbon-13 abundance. Soil Sci. Soc. Am. J. 62, 195–203.

IPCC, 1997. Guidelines for national greenhouse gas inventories. In: Intergovernmental Panel on Climate Change/Organization for Economic Cooperation and Development, OECD, Paris.

Ismail, I., Blevins, R.L., Frye, W.W., 1994. Long-term no-tillage effects on soil properties and continuous corn. Soil Sci. Soc. Am. J. 58, 193–198.

Jacinthe, P., Dick, W., 1997. Soil management and nitrous oxide emissions from cultivated fields in southern Ohio. Soil Till. Res. 41, 221–235.

Jackson, L.E., Calderon, F.J., Steenwerth, K.L., Scow, K.M., Rolston, D.E., 2003. Responses of soil microbial processes and community structure to tillage events and implications for soil quality. Geoderma 114 (3/4), 305–317.

JAWF, 2001. Major World Crop Areas and Climatic Profiles Online Version. Joint Agricultural Weather Facility (posted January 22, 2001; verified July 13, 2004). http://www.usda.gov/oce/waob/jawf/profiles/mwcacp2.htm.

Johnson, R.R., 1988. Soil engaging tool effects on surface residue and roughness with chisel-type implements. Soil Sci. Soc. Am. J. 52, 237–243.

Kammann, C., Grünhage, L., Müller, C., Jocobi, S., Jäger, H.J., 1998. Seasonal variability and mitigation options for N_2O emissions from differently managed grasslands. Environ. Pollut. 102, 179–186.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Barry, E.C., Swan, J.B., Nash, N.S., Jordahl, J.L., 1994. Long-term tillage affects on soil quality. Soil Till. Res. 32, 227–313.

Kucharik, C.J., Roth, J.A., Nabielski, R.T., 2003. Statistical assessment of a paired-site approach for verification of carbon and nitrogen sequestration on Wisconsin conservation reserve program land. J. Soil Water Conserv. 58, 58–67.

Laflen, J.M., Moldenhauer, W.C., 1985. Soybean production and soil erosion problems—North America. In: Shibles, R. (Ed.), Proceedings of the World Soybean Research Conference III. Westview Press, Inc., Boulder, CO, pp. 1166–1174.

Lal, R., 1995. Global soil erosion by water and carbon dynamics. In: Lal, R., Kimball, J., Levine, E., Stewart, B.A. (Eds.), Soils and Global Change. CRC/Lewis Publishers, Boca Raton, FL, pp. 131–142.

Lal, R., 1990. Ridge tillage. Soil Till. Res. 18, 107–111.

Lal, R., 2003. Soil erosion and the global carbon budget. Environ. Int. 29 (4), 437–450.

Lal, R., Fausey, N.R., Eckert, D.J., 1995. Land use and soil management effects on emissions of radiatively active gases from two soils in Ohio. In: Lal, R., Kimball, J., Levin, E., Stewart, B.A. (Eds.), Soil Management and Greenhouse Effect. CRC Press, Boca Raton, FL, pp. 41–59.

Lal, R., Kimble, J.M., Follet, R.F., Cole, V., 1998. Potential of U. S. Cropland for Carbon Sequestration and Greenhouse Effect Mitigation. USDA-NRCS/Ann Arbor Press, Washington, DC/Chelsea, MI.

Lal, R., Logan, T.J., Shipitalo, M.J., Eckert, D.J., Dick, W.A., 1994a. Conservation tillage in the corn belt of the United States. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, Boca Raton, FL, pp. 73–114.

Lal, R., Mahboubi, A.A., Fausey, N.R., 1994b. Long-term tillage and rotation effects on properties of a central Ohio soil. Soil Sci. Soc. Am. J. 58, 517–522.

Layese, M.F., Clapp, C.E., Allmaras, R.R., Linden, D.R., Copeland, S.M., Molina, J.A.E., Dowdy, R.H., 2002. Current and relic carbon using natural abundance 13C. Soil Sci. Soc. Am. J. 167, 315–326.

Lee, J.J., Phillips, D.L., Lui, R., 1993. The effects of trends in tillage practices on erosion and carbon content of soils in the U.S. Cornbelt. Water Air Soil Pollut. 70, 389–401.

Li, C., Narayanan, V., Hariss, R., 1996. Model estimates of nitrous oxide emissions from agricultural lands in the United States. Glob. Biogeochem. Cycl. 10, 297–306.

Linn, D.M., Doran, J.W., 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. Soil Sci. Soc. Am. J. 48, 1267–1272.

Lindstrom, M.J., Nelson, W.W., Schumacher, T.E., 1992. Quantifying tillage erosion rates due to moldboard plowing. Soil Till. Res. 24, 243–255.

Lindstrom, M.J., Nelson, W.W., Schumacher, T.E., Lemme, G., 1990. Soil movement by tillage as affected by slope. Soil Till. Res. 17, 252–264.

Lobb, D.A., Kachanoski, R.G., 1999. Modelling tillage translocation using steppe, near plateau, and exponential functions. Soil Till. Res. 51, 261–277.

Lobb, D.A., Kachanoski, R.J., Miller, M.H., 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using ^{137}cesium as a tracer. Can. J. Soil Sci. 75, 211–218.

Lynch, P.J., Frey, K.J., 1993. Genetic improvement in agronomic and physiological traits of oat since. Crop Sci. 33, 984–988.

Mannering, J., Griffith, D., Richey, C., 1975. Tillage for moisture conservation. Paper No. 75-2523. ASAE Publ.

Mielke, L.K., Doran, J.W., Richards, K.A., 1986. Physical environment near the surface of plowed and no-tilled soils. Soil Till. Res. 7, 355–366.

Mohamoud, Y.M., Ewing, L.K., 1990. Rainfall interception by corn and soybean residue. Trans. ASAE 33, 507–511.

Moldenhauer, W.C., Wischmeier, W.H., 1969. Soybeans in corn–soybean rotations permit erosion but put blame on corn. Crops Soils 21 (6), 20.

Montgomery, J.A., McCool, D.K., Busacca, A.J., Frazier, B.E., 1999. Quantifying tillage translocation and deposition rates due to moldboard plowing in the Palouse region of the Pacific Northwest, USA. Soil Till. Res. 51, 175–187.

Müller, C., Martin, M., Stevens, R.J., Laughlin, R.J., Kammann, C., Ottow, J.C.G., Jäger, H.J., 2002. Processes leading to N_2O

emissions in grassland soil during freezing and thawing. Soil Biol. Biochem. 34, 1325–1331.

Mummey, D., Smith, J., Bluhm, G., 1998. Assessment of alternative soil management practices on N_2O emissions from US agriculture. Agric. Ecosyst. Environ. 70 (1), 79–87.

NCDC, 2001. Freeze/Frost Maps. Freeze Free Period, 90% Probability. National Climate Data Center, National Oceanic and Atmospheric Administration (posted June 22, 2001; verified July 20, 2004). http://www.ncdc.noaa.gov/oa/documentlibrary/freezefrost/frostfreemaps.html.

Ogle, S.M., Jay Breidt, F., Eve, M.D., Paustian, K., 2003. Uncertainty in estimating land use and management impacts on soil organic carbon storage for US agricultural lands between 1982 and. Glob. Change Biol. 9, 1521–1542.

Oschwald, W.R., Siemens, J.C., 1976. Soil erosion after soybeans. In: Hill, L.D. (Ed.), Proceedings of the World Soybean Research Conference. Interstate Printers and Publishers, Danville, IL, pp. 74–81.

Owenby, J., Heim, R.J., Burgin, M., Ezell, D., 2001. Climatography of the U.S. No. 81—Supplement #3 Maps of Annual 1961–1990 Normal Temperature, Precipitation and Degree Days. NOAA (posted May 29, 2001; verified July 13, 2004). http://www.ncdc.noaa.gov/oa/documentlibrary/clim81supp3/clim81.html.

Paul, J.W., Beauchamp, E.G., Zhang, X., 1993. Nitrous and nitric oxide emissions during nitrification and denitrification from manure-amended soil in the laboratory. Can. J. Soil. Sci. 73, 539–553.

Paul, E., Paustian, K., Elliott, E.T., Cole, C.V. (Eds.), 1997. Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America. CRC Press, Boca Raton, FL.

Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manage. 13, 230–244.

Paustian, K., Robertson, G.P., Elliott, E.T., 1995. Management impacts on carbon storage and gas fluxes (CO_2, CH_4) in mid-latitude cropland. In: Lal, R., et al. (Eds.), Soil Management and Greenhouse Effect. CRC Press, Boca Raton, FL, pp. 69–83.

Pedersen, P., Boote, K.J., Jones, J.W., Lauer, J.G., 2004. Modifying the CROPGRO-soybean model to improve predictions for the upper Midwest. Agron. J. 96, 556–564.

Pierce, F.J., Fortin, M.-C., Staton, M.J., 1994. Periodic plowing effects on soil properties in a no-till farming system. Soil Sci. Soc. Am. J. 58, 1782–1787.

Poesen, J., Wesenael, B., Govers, G., Martinez-Fernadez, J., Desmet, B., Vandaele, K., Quine, T., Degraer, G., 1997. Patterns of rock fragment covered generated by tillage erosion. Geomorphology 18, 193–197.

Porter, P., 2004. Use of rye as a cover crop prior to soybean. In: Greenbook Sustainable Energy from Agriculture, Minnesota Department of Agriculture, St. Paul, MN, pp. 67–73.

Prince, S.D., Haskett, J., Steininger, M., Strand, H., Wright, R., 2001. Net primary production of U.S midwest croplands from agricultural harvest yield data. Ecol. Appl. 11, 1194–1205.

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil organic carbon on soil water retention. Geoderma 116, 61–76.

Reeder, R., 2000. Conservation tillage systems and management. In: MWPS-45, 2nd ed., Crop Residue Management with No-till, Ridge-till, Mulch-till and Strip-till, Midwest Plan Service, Iowa State University, Ames, IA, p. 270.

Reicosky, D.C., 1995. Soil variability and carbon dioxide loss after moldboard plowing. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), Proceedings of the Second International Conference on Site-specific Management for Agricultural Systems, Minneapolis, MN. pp. 847–865.

Reicosky, D.C., 1998. Strip tillage methods: Impact on soil and air quality. In: Mulvey, P. (Ed.), Proceedings of the ASSSI National Soils Conference on Environmental Benefits of Soil Management, Brisbane, Australia. pp. 56–60.

Reicosky, D.C., Kemper, W.D., Langdale, G.W., Douglas Jr., C.W., Rasmussen, P.E., 1995. Soil organic matter changes resulting from tillage and biomass production. J. Soil Water Conserv. 50, 253–261.

Reicosky, D.C., Lindstrom, M.J., 1993. Fall tillage method: effect on short-term carbon dioxide flux from soil. Agron. J. 85, 1237–1243.

Reicosky, D.C., Lindstrom, M.J., Schumacher, T.E., Lobb, D.E., Malo, D.D., 2005. Tillage-induced CO_2 loss across an eroded landscape. Soil Till. Res. 81, 183–194.

Rhoton, F.E., Shipitalo, M.J., Lindbo, D.L., 2002. Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. Soil Till. Res. 66, 1–11.

Ridley, A.M., Slattery, W.J., Helyar, K.R., Cowling, A., 1990. The importance of the carbon cycle to acidification of a grazed annual pasture. Aust. J. Exp. Agric. Res. 30, 529–537.

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

Robinson, C.A., Cruse, R.M., Ghaffarzadeh, M., 1996. Cropping systems and nitrogen effects on Mollisol organic carbon. Soil Sci. Soc. Am. J. 60, 264–269.

Ryden, J.C., 1981. N_2O exchange between a grassland soil and the atmosphere. Nature 292, 235–237.

Sauer, T.J., Hatfield, J.L., Prueger, J.H., 1996. Corn residue age and placement effects on evaporation and soil thermal regime. Soil Sci. Soc. Am. J. 60, 1558–1564.

Savabi, M.R., Stott, D.E., 1994. Plant residue impact on rainfall interception. Trans. ASAE 37, 1093–1098.

Schnabel, R.R., Franzluebbers, A.J., Stout, W.L., Sanderson, M.A., Stuedeman, J.A., 2001. The effects of pasture management practices. In: Follett, R.F., Kimble, J.M., Lal, R. (Eds.), The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publishers, Boca Raton, FL, pp. 291–322.

Schomberg, H.H., Steiner, J.L., Unger, P.W., 1994. Decomposition and nitrogen dynamics of crop residues: residue quality and water effects. Soil Sci. Soc. Am. J. 58, 372–381.

Schumacher, T.E., Lindstrom, M.J., Schumacher, J.A., Lemme, G.D., 1999. Modelling spatial variation and productivity due to tillage and water erosion. Soil Till. Res. 51, 331–339.

Shelton, D.P., Dickey, E.C., Kachman, S.D., Fairbanks, K.T., 1995. Corn residue cover on the soil surface after planting for various tillage and planting systems. J. Soil Water Conserv. 50, 399–404.
Shelton, D.P., Kachman, S.D., Dickey, E.C., Fairbanks, K.T., Jasa, P.J., 1994. Tillage and planting system, stalk chopper, and knife applicator influences on corn residue cover. Trans. ASAE 10, 255–261.
Siemens, J.C., Oschwald, W.R., 1978. Corn–soybean tillage systems: erosion control, effects on crop production, costs. Trans. ASAE 21, 293–302.
Siemens, J.C., Oschwald, W.R., 1976. Erosion for corn tillage systems. Trans. ASAE 19, 69–72.
Six, J., Ogle, S., Breidt, F., Conant, R., Mosier, A., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term. Glob. Change Biol. 10, 155–160.
Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000. Soil structure and organic matter. I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64, 681–689.
Sloneker, L.L., Moldenhauer, W.C., 1977. Measuring the amounts of crop residue remaining after tillage. J. Soil Water Conserv. 32, 231–236.
Smith, J.A., Yonts, C.D., Rath, M.D., Bailie, J.E., 1990. Mass of crop residue and its relationship with soil cover for a corn, dry bean, and sugarbeet rotation. Trans. ASAE 33, 1503–1508.
Soil Survey Staff, 1981. Land resource regions and major land resource areas of the United States. In: Agriculture Handbook 296, Revised Edition, United States Department of Agriculture, Soil Conservation Service, Washington, DC, p. 156.
Sperow, M., Eve, M., Paustian, K., 2003. Potential soil C sequestration on US agricultural soils. Clim. Change 57, 319–339.
Stott, D.E., Elliott, L.F., Papendick, R.I., Campbell, G.S., 1986. Low temperature or low water potential effects on the microbial decomposition of wheat residue. Soil Biol. Biochem. 18, 577–582.
Stout, W.L., 1992. Water-use efficiency of grasses as affected by soil, nitrogen, and temperature. Soil Sci. Soc. Am. J. 56, 897–902.
Stout, W.L., Jung, G.A., 1995. Effects of soil and environment on biomass accumulation of switch grass. Agron. J. 87, 663–669.
Stout, W.L., Jung, G.A., 1992. Influences of soil environment on biomass and nitrogen accumulation rates of orchardgrass. Agron. J. 84, 1011–1019.
Tester, C.F., 1990. Organic amendment effects on physical and chemical properties of a sandy soil. Soil Sci. Soc. Am. J. 54, 827–831.
Todd, R., Klocke, N.L., Dickey, E.C., Bauer, D., 1988. Surface cover from corn residue on sandy soils. Appl. Eng. Agric. 4, 234–236.
Tollenaar, M., Lee, A.F., 2002. Yield potential, yield stability and stress tolerance in maize. Field Crop Res. 75, 161–169.
Triplett Jr., G.B., Van Doren Jr., D.M., Schmidt, B.L., 1968. Effect of corn (*Zea mays* L.) stover mulch on no-tillage corn yield and water infiltration. Agron. J. 60, 236–239.
USDA-NASS, 1997. 1997 Census of Agriculture. United States Department of Agriculture-National Agriculture Statistic Service, Research and Development Division (verified July 13, 2004). http://www.nass.usda.gov/research/index.htm.
USDA-NASS, 2003. USDA-National Agricultural Statistics Service, Historical Data. United States Department of Agriculture-National Agriculture Statistic Service, Research and Development Division (posted 2003; verified July 20, 2004). http://www.usda.gov/nass/pubs/histdata.htm.
USDA-NRCS, 1997a. Broad land cover/use, by state. United States Department of Agriculture-Natural Resources Conservation Service, Resource Assessment Division (posted June 2001; verified July 13, 2004). http://www.nrcs.usda.gov/technical/land/cover_use.html.
USDA-NRCS, 1997b. MLRA Interactive Map. Soil Information for Environmental Modeling and Ecosystem Management. United States Department of Agriculture-Natural Resources Conservation Service (posted December 15, 1998; verified July 12, 2004). http://soils.usda.gov/survey/geography/mlra/index.html.
USDA-NRCS, 2001. National Resources Inventory 2001 Annual NRI. United States Department of Agriculture, Natural Resources Conservation Service (verified July 12, 2004). http://www.nrcs.usda.gov/technical/land/nri01/.
Van den Pol-van Dasselaar, A., Lantinga, E.A., 1995. Modelling the carbon cycle of grasslands in the Netherlands under various management strategies and environmental conditions. Neth. J. Agric. Sci. 43, 183–194.
Van Muysen, W., Govers, G., Bergkamp, G., Roxo, M., Poesen, J., 1999. Measurement and modelling of the effects of initial soil conditions and slope gradient on soil translocation by tillage. Soil Till. Res. 51, 303–316.
Velthof, G.L., Jarvis, S.C., Stein, A., Allen, A.G., Oenema, O., 1996. Spatial variability of nitrous oxide fluxes in mown and grazed grasslands on a poorly drained clay soil. Soil Biol. Biochem. 28, 1215–1225.
Velthof, G.L., Oenema, O., 1995. Nitrous oxide fluxes from grassland in the Netherlands. II. Effects of soil, nitrogen fertilizer application and grazing. Eur. J. Soil Sci. 46, 541–549.
Venterea, R., Rolston, D., 2000. Mechanisms and kinetics of nitric and nitrous oxide production during nitrification in agricultural soil. Glob. Change Biol. 6, 303–316.
Venterea, R., Rolston, D., Cardon, Z., 2005. Effect of soil moisture, physical and chemical factors on abiotic nitric oxide production. Nutr. Cycl. Agroecosyst., in press.
Vetsch, J.A., Randall, G.W., 2004. Corn production as affected by nitrogen application timing and tillage. Agron. J. 96, 502–509.
Vitosh, M.L., Davis, J.F., Knezek, B.D., 1973. Long-term effects of manure, fertilizer, and plow depth on chemical properties of soils and nutrient movement in a monoculture corn system. J. Environ. Qual. 2, 296–299.
Wagner, L.E., Nelson, R.G., 1995. Mass reduction of standing and flat crop residues by selected tillage implements. Trans. ASAE 38, 419–427.
Waksman, S.A., Gerretsen, F.C., 1931. Influence of temperature and moisture upon the nature and extent of decomposition of plant residues by microorganisms. Ecology 12, 33–60.

Walker, S.L., Leath, S., Murphy, J.P., Lommel, S.A., 1998. Selection for resistance and tolerance to oat mosaic virus and oat golden stripe virus in hexaploid oats. Plant Dis. 82, 423–427.

Wander, M.M., Bidart, M.G., Aref, S., 1998. Tillage impacts on the depth distribution of total and particulate organic matter in three Illinois soils. Soil Sci. Am. J. 62, 1704–1711.

Wedin, D.A., Tilman, D., 1996. Influence of nitrogen loading and species composition on the carbon balance in grasslands. Science 274, 1720–1723.

West, C.P., Mallarino, A.P., Wedin, W.F., Marx, D.B., 1989. Spatial variability of soil chemical properties in grazed pasture. Soil Sci. Soc. Am. J. 53, 784–789.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946.

Wilhelm, W.W., Johnson, J.M.F., Hatfield, J.L., Voorhees, W.B., Linden, D.R., 2004. Crop and soil productivity response to corn residue removal: a literature review. Agron. J. 96, 1–17.

Williams, D.L., Ineson, P., Coward, P.A., 1999. Temporal variations in nitrous oxide fluxes from urine-affected grasslands. Soil Biol. Biochem. 31, 779–788.

Wilts, A.R., Reicosky, D.C., Allmaras, R.R., Clapp, C.E., 2004. Long-term corn residue effects: Harvest alternatives, soil carbon turnover, and root-derived carbon. Soil Sci. Soc. Am. J. 68, 1342–1351.

Woodruff, N.P., Fenster, C.R., Chepil, W.S., Siddoway, F.H., 1965. Performance of tillage implements in a stubble mulch system. I. Residue conservation. Agron. J. 57, 45–49.

Yang, H.S., Dohermann, A., Lindquist, J.L., Walters, D.T., Arkebauer, T.J., Cassman, K.G., 2004. Hybrid-maize—a maize accumulation model that combines two crop modeling approaches. Field Crop Res. 87, 131–154.

Yang, X.M., Wander, M.M., 1999. Tillage effects on soil organic carbon distribution and storage on a silt loam in Illinois. Soil Till. Res. 52, 1–9.