Soil Organic Carbon Dynamics in the Pendleton Long-Term Experiments: Implications for Biofuel Production in Pacific Northwest

Stephen Machado*

Symposium

ABSTRACT

Use of crop residues for biofuel production raises concerns on how removal will impact soil organic carbon (SOC). Information on the effects on SOC is limited and requires long-term experimentation. Fortunately, Pendleton long-term experiments (LTEs), dating to the 1930s, provide some answers. This study compared crop residue inputs and SOC balance in conventional tillage (CT) winter wheat (*Triticum aestivum* L.)–summer fallow (WW-SF) systems with annual rotation of WW and spring pea (*Pisum sativum* L.). The WW-SF consisted of crop residue (CR-LTE) (0–90 N ha^{-1} yr^{-1}, 11.2 Mg ha^{-1} yr^{-1} of steer (*Bos taurus*) manure and 1.1 Mg ha^{-1} yr^{-1}of pea vines additions, residue burning, and tillage fertility (TF-LTE) (tillage- plow, disc, sweep, and N (0–180 kg ha^{-1})). Winter wheat–pea (WP-LTE) rotation treatments included maxi-till (MT-disc/chisel), fall plow (FP), spring plow (SP), and no-till (NT). Soils were sampled (0–60-cm depth) at 10-yr intervals, and grain yield and residue data collected every year. In WW-SF systems, SOC was maintained only by manure addition and depleted at a rate of 0.22 to 0.42 Mg ha^{-1} yr^{-1} in other treatments. In WP-LTE, MT, FP, SP, and NT treatments increased SOC at the rate of 0.10, 0.11, 0.02, and 0.89 Mg ha^{-1} yr^{-1}, respectively. Minimum straw biomass to maintain soil organic carbon (MSB) in the CR-LTE, TF-LTE, and WP-LTE was 7.8, 5.8, and 5.2 Mg ha^{-1} yr^{-1}, respectively. Winter wheat-SF straw production was lower than MSB, therefore residue removal would exacerbate SOC decline. Harvesting straw residues under NT continuous cropping systems is possible when MSB and conservation requirements are exceeded.

The search for alternative energy has increased interest in the production of biofuels from more than 453.5 Tg of crop residues produced each year in the United States. Crop residues play an important role in soil conservation and SOC buildup. The removal of crop residues for biofuel production could negatively impact soil quality and productivity if the requirements for SOC maintenance and soil conservation are not met. The exact amounts of crop residues that could be retained will depend on cropping system and residue management practices, soil type, and climate. Information on the impacts of crop residue removal is limited and mostly based on short-term studies (Mann et al., 2002; Blanco-Canqui and Lal, 2009a; Blanco-Canqui, 2010). Available studies indicated that residue removal negatively impacted soil fertility and structure (Blanco-Canqui and Lal, 2009b), SOC (Wilts et al., 2004; Blanco-Canqui and Lal, 2009b), soil erosion (Lindstrom, 1986) and crop productivity (Wilhelm et al., 2004; Lal, 2007; Wilhelm et al., 2007). Wilhelm et al. (2007) estimated that between 5.2 and 12.5 Mg ha^{-1} of crop residues were required just to maintain SOC in NT continuous corn and CT corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation, respectively. Lafond et al. (2009) reported that removing <40% of total aboveground residues (1907 kg ha^{-1}) in 2 out of 3 yr did not affect SOC in 50 yr in medium to heavy textured soils. Johnson et al. (2006) reported that an input of about 2.5 and 1.8 Mg C ha^{-1} yr^{-1} was required to maintain SOC under CT and NT practices, respectively. In the Pacific Northwest (PNW), where WW-SF rotation is the predominant cropping system in the low to medium precipitation regions (150–400 mm) of north-central Oregon and south-central Washington, it is estimated that between 3 and 5 Mg ha^{-1} of crop residues should be retained in the field for conservation purposes (Banowetz et al., 2007) and probably another 5 Mg ha^{-1} yr^{-1} for SOC maintenance (Rasmussen et al., 1980; Rasmussen and Smiley,. 1997). Changes in SOC have been highly correlated with residue input in WW-SF system in the PNW (Rasmussen and Parton, 1994) indicating that this system will be particularly sensitive to residue removal. To avoid detrimental effects of residue removal only crop residues in excess of the minimum amounts required to maintain SOC levels and for conservation purposes should be available for other uses including biofuel production. However, information on the amount of residue that can be removed without negative impacts to SOC sequestration and soil productivity in the PNW is limited. This information is needed to determine whether crop residues could be harvested for biofuels production. An indirect way to provide the same information is to determine whether current PNW cropping systems are sequestering or losing SOC.

Tillage, fertility, crop rotations, and cropping intensity influence the rate at which C is added to or removed from soil (Franzluebbers, 2004). Carbon balance is influenced by numerous and complex interactions among plant, soil, water, and soil microbes.

Oregon State Univ., Columbia Basin Agricultural Research Center, P.O. Box 370, Pendleton, OR 97801. Received 3 May 2010. *Corresponding author (stephen.machado@oregonstate.edu).

Published in Agron. J. 103:253–260 (2011)
Published online 9 Dec 2010
doi:10.2134/agronj2010.0205s

Copyright © 2011 by the American Society of Agronomy, 5585 Guilford Road, Madison, WI 53711. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Abbreviations: CR, crop residue experiment; CT, conventional tillage; FP, fall plow treatment; LTE, long-term experiment; MSB, minimum straw biomass required to maintain soil organic carbon; MSC, minimum amount of straw biomass required to maintain soil organic carbon; MT, maxi-till treatment; NT, no-tillage; PNW, Pacific Northwest; SOC, soil organic carbon; SP, spring plow treatment; TF, tillage fertility experiment; WP, wheat–pea rotation; WW-SF, winter wheat–summer fallow.

Table 1. Long-term experiments at Pendleton, OR.

Experiment	Treatments	Year initiated
Perennial grassland	none	1931
Continuous cereal	fertility (N), crop, tillage	1931
Residue management	fertility (N, manure, pea vine), burning	1931
Tillage–fertility	tillage, fertility (N)	1940
Wheat–pea	tillage, fertility (N, liming)	1963
No-till wheat	fertility (N)	1982
Moro long-term experiments	tillage, crop rotations	2003

Effects of cropping systems on these interactions are often slow and only well-established long-term experiments (LTEs) provide the understanding of the processes involved in SOC dynamics. Such LTEs are few and likewise information to ascertain the effects of residue removal on SOC dynamics and soil productivity is limited. Fortunately some information on this matter could be gleaned from existing LTEs at the Oregon State University (OSU), Columbia Basin Agricultural Research Center (CBARC) near Pendleton, OR, some of which date back to the 1930s.

The objectives of this study were (i) to estimate the carbon balance of the LTEs and (ii) from this analysis define cropping systems that can be targeted for straw residue removal for biofuel production in the PNW.

MATERIALS AND METHODS

The Pendleton LTEs are located at OSU CBARC near Pendleton, OR. The research center is located in the Columbia Plateau between the Cascade and Rocky Mountains (45°42' N, 118°35'60" W, elevation 438 m). The climate is semiarid, but partially influenced by maritime winds from the Pacific Ocean. Winters are cool and wet, and summers are hot and dry. Annual precipitation averages 400 mm, with nearly 70 to 80% falling between 1 September and 1 April. Average temperature is 10°C, but ranges from –1°C in January to 21°C in July. The Pendleton LTEs are located on a gently sloping landscape, with slopes ranging from 0 to 5%. Soils are Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxerolls) that developed from loess deposits overlying basalt. The area was first broken for cultivation in the mid-1880s, and had been farmed for about 50 yr when the research center was established in 1929. Several long-term experiments have been established at CBARC (Table 1). For the present study, two WW-SF cropping systems, the CR-LTE and the TF-LTE, and one continuous annual cropping system, the WP-LTE, were evaluated. The design and history of the Pendleton LTEs are briefly summarized below. The Pendleton LTEs were described in detail by Rasmussen and Smiley (1997).

Table 2. Historical residue treatment (RT) and N-fertility treatments (N) of the crop residue management experiment since being established in 1931.

Treatment no.	Organic-N addition	1931–1966		1967–1978		1979 to present	
		RT†	N‡	RT	N	RT	N
1	–§	–	–	–	–	–	–
2	–	FD	0	NB	45	SB	45
3	–	SD	0	NB	90	SB	90
4	–	NB	34	NB	45	NB	45
5	–	NB	34	NB	90	NB	90
6	–	FB	0	FB	0	FB	0
7	–	SB	0	SB	0	SB	0
8	manure¶	NB	0	NB	0	NB	0
9	pea vines#	NB	0	NB	0	NB	0
10	–	NB	0	NB	0	NB	0

† RT = Residue treatment: FD = fall disk, SD = spring disk, NB = no burn, FB = fall burn, SB = spring burn.

‡ N rate (kg ha^{-1}); applied early October of crop year.

§ 2.24 Mg ha^{-1} field weight alfalfa hay applied to plot 11 from 1939–1949 1–3 d before plowing

¶ Manure = (22.4 Mg ha^{-1} wet wt; 47.5% dry matter; 1.69 Mg C ha^{-1} and 0.14 Mg N ha^{-1}; applied 1–3 d before plowing in April or May of plow year.

Pea vines = (2.24 Mg ha^{-1} field weight; 87.8% dry matter; 0.82 Mg C ha^{-1} and 0.037 Mg N ha^{-1}; applied 1–3 d before plowing.

Crop Residue Management

The CR-LTE was the most comprehensive of the Pendleton LTEs. It was established in 1931 and has had only two major modifications (1967, 1979) (Table 2). The objective of the experiment was to determine the effects of N application, residue burning, and pea vine and manure application on soil chemical and physical properties, and crop productivity under the traditional WW-SF system using conventional moldboard plow tillage (CT). Treatment history is shown in Table 2. The experimental design was an ordered block with nine treatments and two replications. The experiment had duplicate sets of experiments offset by 1 yr so that all phases of the rotation are represented every year. Plot size was 12 by 40 m. A single medium-tall variety (Rex M-1) was grown from 1931 to 1966. Modern semi-dwarf varieties have been grown since (Nugaines 1967–1973; Hyslop 1974–1978; Stephens 1979–1991; Malcolm 1992–1995, and Stephens 1996–2005).

Winter wheat was seeded in mid-October and harvested in mid-July. Fall stubble burns were implemented in late September. Spring stubble burns were implemented and organic amendments (manure and pea vines) applied in the spring of the fallow year (late March–early April from 1931–1994; late April–early May since then). Manure and pea vines were applied at a rate of 22.4 and 2.24 Mg ha^{-1} biennially, respectively. Late-winter or early-spring herbicides were used to control vegetative growth in wheat stubble until plots were plowed. Plots were plowed 20-cm deep within 3 d after spring burning. Soil was then smoothed with a field cultivator or harrow. Weeds were controlled by tillage during the fallow phase and with herbicides during the crop phase. For treatments receiving fertilizer, N at the rate of 45 and 90 kg ha^{-1} was applied 5 to 15 d before seeding of wheat.

Delayed spring tillage for fallow was implemented in 1994 in contrast to previous plowing in late March. Herbicide were applied in either late fall or early spring to control downy brome and volunteer wheat in wheat stubble. The herbicide application permitted delaying spring plowing until late April or early May when soil was drier. This change avoided spring tillage when soils were wet and eliminated two to four tillage operations. The SOC content was measured about every 10 yr (1931, 1941, 1951, 1964, 1976, 1986, 1995, and 2005). In the present study SOC in the 0- to 60-cm depth profile from 1976 to 2005 was evaluated (30 yr). Before 1976 some SOC data sets exist as treatment means that could not be subjected to statistical analyses. Crop biomass (total dry matter, grain yield, straw yield) was determined every year since1977. In the present study only crop biomass data from 1982 to 2005 (24 yr) was evaluated to determine the yearly mean crop yield and biomass production that could be related to SOC. Some data sets from 1977 to 1981 were incomplete. Carbon additions were derived from straw residue by dividing by 2.38 (wheat straws at the Pendleton station consistently contained about 42% C during the studied period). Rasmussen et al. (1980) found the same percentage of C in wheat straws in the 1967 to 1976 period. Carbon additions in manure and pea vines were based on a 27-yr period (1967–2002). In this period manure and pea vines added an average of 1.69 and 0.82 Mg C ha^{-1} yr^{-1}, respectively.

Tillage Fertility

The TF-LTE evaluated tillage and N treatments on crop and crop productivity under WW-SF cropping system. The experiment was established in 1940 and has been modified in 1952, 1962, and 1988 (Table 3). This experiment had only one set of plots, therefore yield and biomass were obtained only in odd years. Treatment history is shown in Table 3. The experimental design was a randomized block split-plot, with three replications. Three primary tillage systems, the moldboard plow, offset disc, and subsurface sweep were the main plots and fertility (N) levels (0, 45, 90, 135, 180 kg ha^{-1}) were subplots. Individual plot size was 5.5 by 40 m.

Primary tillage was conducted in April. Secondary tillage and other cultural operations were the same for all treatments. All plots were cultivated and harrowed to a depth of 10 to 15 cm following primary tillage and then rod-weeded as needed to control weeds and maintain seed zone moisture. Nitrogen fertilizer was applied about 1 October and winter wheat seeded about 10 October. Nitrogen applied as ammonium nitrate (NH_4NO_3) (21–0–0–24S) from 1963 to 1987, and thereafter as urea $CO(NH_2)_2$–ammonium nitrate (32–0–0). Weeds were controlled by mechanical and chemical methods. Medium-tall soft white winter wheat (Rex M-1) was grown from 1940 to 1962, and semi-dwarf soft white WW since (Nugaines, Hyslop, Malcolm, and Stephens). The SOC content of soil was measured about every 10 yr since 1984. In the present study SOC in the 0- to 60-cm depth profile from 1984 to 2005 (22 yr) was evaluated. Crop biomass (total dry matter, grain yield, straw yield) was determined every year since 1977. In the present study only crop biomass data from 1989 to 2003 (15 yr) was evaluated to determine the yearly mean crop yield and biomass production that could be related to SOC. Carbon additions were derived from straw residue by dividing by 2.38. Time spans for biomass and SOC data do not match because biomass data sets were incomplete in some years.

Wheat–Pea Rotation

The wheat–pea LTE was established in 1963, with modifications in 1972, 1976, and 1989. Crop rotation was WW–pea. Treatment history and plot layout is shown in Table 4. The experimental design was a randomized block with four replications. Each replication contains eight plots (four treatments duplicated within each replication). Duplicate treatments offset by a year allow yearly data collection for both wheat and pea. Individual plot size was 7.2 by 36.5 m. Tillage intensity ranges from maximal- to minimal-inversion of crop residue. The current tillage treatments were (i) MT, (ii) FP, (iii) SP, and (iv) NT. Details of these treatments are described in Machado et al. (2008). Briefly, MT involved roto-tilling the land in the fall, and sweep and disc tillage in the spring before seeding pea. After pea harvest plots were cultivated with a sweep and chisel plowed before seeding wheat. The FP involved moldboard plowing in the fall and cultivating one to three times with a spring-tooth cultivator in the spring before seeding peas. Before seeding wheat, plots were moldboard-plowed in the summer after pea harvest followed by secondary tillage using a spring-tooth cultivator. The SP was identical to FP before sowing wheat but plots were plowed in the spring before seeding peas. No-till involved no tillage and weeds were controlled by herbicides. Pea vines and wheat residues were now left on the plot rather than removed as in earlier years. Semi-dwarf soft white WW was seeded in the fall (usually in October) when soil moisture was sufficient for germination using a double disk drill with 18-cm row spacing. Spring pea was seeded in late March or early April, and harvested in June or July. The type of pea grown was changed from fresh-green processing to dry edible seed in 1989. From 1963 to 1988, wheat received 45–90 kg N ha^{-1} as ammonium nitrate (NH_4NO_3 [34–0–0]) broadcast before seeding. In 1989–1990, each wheat plot received 22 kg N ha^{-1} (16–20–0–14S). In 1991–1992, one-half of each plot received 90 kg N ha^{-1} and the other half received no additional N. Nitrogen application was reversed in 1993–1994, with the half receiving 90 kg N ha^{-1} for the previous wheat crop receiving no additional N 2 yr later. From then on to the present all wheat plots have received 90 kg N ha^{-1} every wheat year. Pea received 22 kg N ha^{-1} as either ammonium sulfate (21–0–0–24S) or ammonium phosphate (16–20–0–14S) broadcast every pea crop year.

The SOC content of soil was measured in 1995 and 2005. In the present study SOC in the 0- to 60-cm depth profile was evaluated. Crop biomass (total dry matter, grain yield, straw yield) was determined every year since 1984. In the present study 10 yr of data (1995–2004) were evaluated to determine the yearly

Table 3. Historical tillage and N treatments of the tillage fertility (TF) experiment since being established in 1940.

Primary treatment (tillage)		Tillage depth
Symbol	Type	
		cm
MP†	moldboard plow	23
DI	offset disc	15
SW	subsurface sweep	15

Sub-treatment (fertility)					
N	Sulfur application	1941–1952	1953–1962	1963–1988	1989-present
		N rate, kg ha^{-1}			
1	no	0	0	45	0
2	yes	11	34	45	45
3	no	0	0	90	90
4	yes	11	34	90	90
5	yes	11	34	135	135
6	yes	11	34	180	180

† Nitrogen applied 7 to 14 d before seeding as ammonium sulfate ($(NH_4)_2SO_4$), 21–0–0–24 (N–P–K–S) from 1941 to 1962, ammonium nitrate (NH_4NO_3), 26–0–0 (N–P–K), from 1963 to 1988, and urea ($(NH_2)_2CO$)–ammonium nitrate solution since 1989. Nitrogen broadcast from 1941 to 1988, and banded 15-cm deep with 30-cm row spacing since 1989.

Table 4. Current treatments of the wheat–pea rotation experiment since the last changes in 1989.

Treatment		Primary tillage	
No.	Identification	Wheat stubble	Pea vines
1	Max till (MT)	Disk (fall)	Chisel (fall)
2	Fall plow (FP)	Plow (fall)	Plow (fall)
3	Spring plow (SP)	Plow (spring)	Plow (fall)
4	No-till (NT)	No-till	No-till

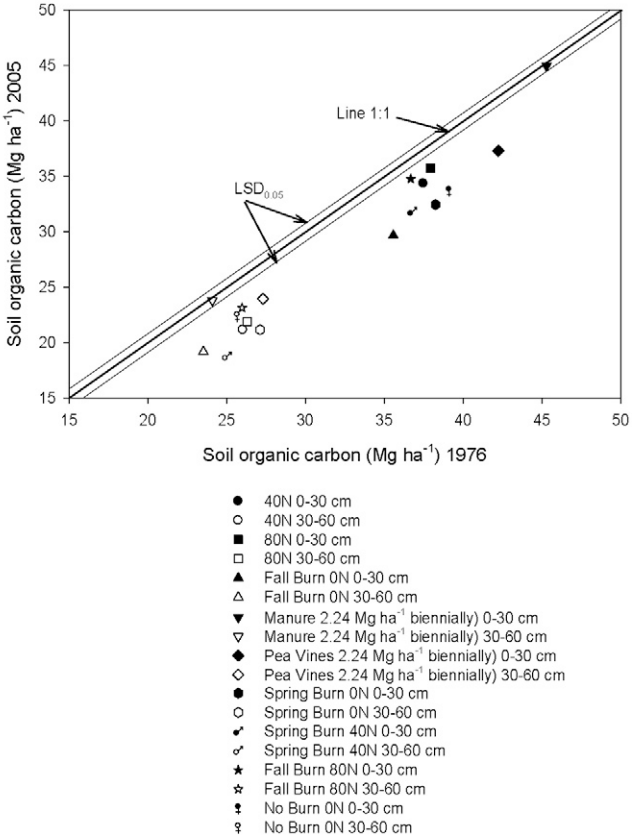

Fig. 1. Crop residue management effects on soil organic carbon changes in the crop residue long-term experiment from 1976 to 2005 at the Oregon State University, Columbia Basin Agricultural Research Center, Pendleton, OR.

mean crop yield and biomass production that could be related to SOC. Carbon additions were derived from both wheat and pea straw residue by dividing by 2.38. Carbon additions from wheat and pea straw were based on a 2-yr period (1995–1996) in which both wheat and pea straw contained an average of 42% C.

Soil Organic Carbon Analyses

Soil samples for SOC determination were taken every 10 yr from most of the LTEs using hand probes in the early years and the Giddings Probe (Giddings Machine Co, Inc., Fort Collins, CO) in recent years. Soil samples were taken at 10-cm intervals in the top 30 cm and at 30-cm intervals down to restricting zone. Before 1976 C was measured using the Walkley–Black titration method (Nelson and Sommers, 1982). After 1976, C was determined by combustion methods. From 1976 to 1994 C was measured using a LECO C Analyzer (Model CN200, LECO Corp., St. Joseph, MI). From1995 to the present C was measured using a Thermo Finnigan, N and C Soil Analyzer (Flash EA 1112 series, Thermo-Finnigan, San Jose, CA).

Residue at Seeding

Surface residue cover reported in the present study was measured in the 1980s in the TF-LTE and in 2004 and 2005 in the WW-WP LTEs using the line-transect method (Laften et al., 1981). A 15 m steel tape was placed diagonally at a 45° angle across crop rows after seeding and residues intersecting with the tape at every 30-cm interval counted. This procedure was repeated at least two to four times per plot depending on plot size. Percent residue cover was derived from these data.

Grain Yield and Biomass

Data on yield and yield components were collected from each plot and crop. At harvest, four bundle samples were obtained from each plot. Each bundle consisted of four drill rows, 1 m long. The bundles were hand cut, weighed to obtain total bundle dry matter. The bundles were then threshed and grain weight measured. Straw weight was obtained by difference. A Hege plot combine (Wintersteiger AG, Eging am See, Germany) was used to harvest the remaining crop. Bundle yields were highly correlated to combine yields ($r = 0.94$, $P < 0.001$).

Statistical Analyses

Data from CR-LTE and TF-LTE and the WW-WP-LTE within each year and across years were analyzed using PROC GLM or MIXED procedures in Statistical Analysis System (SAS) program (SAS Institute, 2003). Simple correlations (Pearson) among variables were calculated using PROC CORR in SAS. Means were separated using LSD at the 0.05 probability level. The minimum amount of carbon additions required to maintain soil organic carbon (MSC) in the respective time spans was estimated by a simple linear relationship between changes in SOC and organic carbon additions from manure, pea vines, and straw residues in each time span (Larson et al., 1972; Johnson et al., 2006).

RESULTS AND DISCUSSION

Dynamics of SOC were influenced by the crop rotation, crop intensity, and tillage system. Results showed a clear distinction between the WW-SF and annual cropping in SOC dynamics. The WW-SF cropping system generally depleted SOC compared to annual cropping systems.

Wheat-Summer Fallow

Differences in SOC levels were observed in both the 0- to 30-cm and the 30- to 60-cm depths (Fig. 1) and in the whole 0- to 60-cm depth profile (Table 5) in the CR-LTE, a WW-SF based cropping system. In both depth profiles, the biennial application of 22.4 Mg ha^{-1} of manure maintained SOC levels from 1976 to 2005. The addition of 2.24 Mg ha^{-1} of pea vines biennially or the annual application of N at the rate of 45 to 90 kg ha^{-1} could not prevent the depletion of SOC during this period (1976–2005). The 0 N, 40 N, 80 N, and pea vine treatments lost 0.29, 0.26, 0.22, and 0.28 Mg ha^{-1} yr^{-1} or 13.4, 12.4, 10.4, and 11.9% of 1976 SOC in 30 yr, respectively (Table 5). The 0 N Fall Burn treatment lost the most SOC, 0.34 Mg ha^{-1} yr^{-1} or 17.3% of the 1976 SOC value. These results confirm earlier observations that indicated that SOC was on the decline in all CR-LTE treatments except where manure was applied starting in 1931 (Rasmussen and Collins, 1991; Rasmussen and Parton, 1994; Rasmussen et al., 1998). The depletion of SOC under the WW-SF system was mainly attributed to the limited amount of biomass returned to the soil. In this WW-SF system only one crop was grown in 2 yr and not enough straw biomass to maintain SOC was produced in all treatments (Table 5). Increasing N levels both from synthetic N sources and from pea vines significantly increased biomass production but the total amounts produced per year were obviously not sufficient to maintain SOC levels (Table 5). Total SOC in the 0- to

60-cm depth profile observed in 2005 had significantly decreased compared to levels observed in 1976 (Table 5). Only the manure treatment that added C through both manure (22.4 Mg ha^{-1} biennially) and high straw biomass (4.8 Mg ha^{-1}yr^{-1}) maintained SOC levels (Fig. 1, Table 5). This treatment has maintained SOC levels since 1931 (Rasmussen and Collins, 1991; Rasmussen and Parton, 1994; Rasmussen et al., 1998). Residue burning, a practice that was very common in the PNW till the 1990s but now practiced on a limited scale, had the most negative impact on SOC (Fig. 1) and total biomass production (Table 5). Burning destroys organic compounds leaving ash that does not contribute to SOC (Rasmussen et al., 1980; Malhi and Kutcher, 2007). In addition to reducing the amount of residues returned to the soil, the WW-SF rotation using CT (moldboard plowing) as was the case in CR-LTE exacerbated SOM loss and CO_2 emission by enhancing oxidation of buried crop residues (Rasmussen and Parton, 1994; Reicosky et al., 1995; Rasmussen et al., 1980, 1998).

In the TF-LTE, another WW-SF cropping system involving tillage and N treatments, there was no interaction between tillage and fertilizer on SOC levels from 1984 to 2005. Increasing N from to 90 kg ha^{-1} increased total plant biomass and grain yield (Table 6). Further increases in N up to 180 kg ha^{-1} did not result in further increases in both parameters. The increase in total biomass, however, did not influence SOC levels measured in 1984, 1995, and 2005. Although biomass increased with increase in N levels, it is apparent that the amounts produced (one crop in 2 yr) were not sufficient to influence SOC levels. Overall SOC decreased by 0.47, 0.34, 0.40, and 0.48 Mg ha^{-1} yr^{-1} or by 16, 12, 14, and 16% in 22 yr (1984–2005) in the 45, 90, 135, and 180 N treatments, respectively (Table 6).

Soil organic carbon decreased in the 0- to 30-cm soil depth profile under all tillage treatments involving plow, disc, and sweep methods in TF-LTE (Fig. 2). In the 30- to 60-cm depth profile, SOC in the plow and disc treatments decreased significantly while SOC observed in 1984 under the sweep was maintained till 2005. Overall, the 22 yr of plow, disc, and sweep treatments decreased SOC by 0.37, 0.46, and 0.46 Mg ha^{-1} yr^{-1} or by 13, 15, and 15% of the 1984 levels, respectively (Table 7). The plow treatment had significantly higher total biomass production than the disc and sweep treatments in the studied period (1989–2003) (Table 7). However, total SOC in the 0- to 60-cm depth profile under the plow treatments was the lowest and significantly so in 1995 (Table 7). Soil organic carbon in the disc treatment was the highest in all years although not significantly so in 1984 and 2005. When only the 0- to 30-cm zone is considered SOC measured in 1984, 1995, and 2005 was significantly higher in the disc treatment and lowest in the plow treatment (Fig. 2). The results indicated that an increase in biomass production per se did not guarantee an increase in SOC. Residue management appeared to have an influence on SOC levels. The plow treatment with the highest biomass production also had the lowest residue cover probably indicating that more residues were incorporated in this treatment than in the disc and sweep treatments. All residue cover measurements were taken after implementation of tillage treatments on flat biomass that has been shown to relate reasonably well to residue weight (McCool et al., 1995; Steiner et al., 2000). Incorporation of residues into soil has been shown to accelerate depletion of SOC. The loss of SOC through increased biological oxidation under CT conditions has been quantified (Rasmussen et al., 1980, 1998; Rasmussen and Parton, 1994; Reicosky et al., 1995). In a study that compared tillage practices, plowing buried all residues and increased SOC loss compared to discing, chiseling, and NT (Reicosky et al., 1995).

Results from the above two CT based WW-SF LTEs showed that this system lost SOC from 1976 to 2005. This observation is a continuation of the decline in SOC observed by Rasmussen et al. (1980) in the WW-SF cropping system from 1931 to 1976. Other studies have also demonstrated that fallow is associated with loss of SOC (Rasmussen and Smiley, 1997; West and Post, 2002; Machado et al., 2006). The main reason for the loss of SOC was the

Table 5. Crop residue management effects on crop biomass, grain yield (1982–2004), and soil organic carbon (SOC) (1976–2005) in the Crop Residue long-term experiment (LTE) (winter wheat–summer fallow).

N†	Burn	TDM†	GYD†	SDM†	SOC‡		Significance level§
		1982–2004			1976	2005	
kg ha^{-1}		—— Mg ha^{-1} yr^{-1}——			—— Mg ha^{-1}——		
0	NB	4.0d	1.4d	2.6d	64.8ab	56.1c	***
40	NB	5.8c	2.1c	3.7c	63.5ab	55.6c	**
80	NB	6.4b	2.4b	4.1b	64.3ab	57.6bc	*
Pea¶	NB	5.9c	2.1c	3.8bc	69.6a	61.3b	**
Manure#	NB	7.6a	2.8a	4.8a	69.4a	68.8a	ns††
0	FB	3.8d	1.3d	2.5d	59.1b	48.9d	**
se		0.15	0.05	0.1	2.3	1.5	

* Indicates that SOC means in 1976 and 2005 are significantly different at the 0.05 probability level.

** Indicates that SOC means in 1976 and 2005 are significantly different at the 0.01 probability level.

*** Indicates that SOC means in 1976 and 2005 are significantly different at the 0.001 probability level.

† N, nitrogen; TDM, total bundle dry matter; GYD, combine grain yield; SDM, bundle straw yield, SOC, soil organic carbon.

‡ Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

§ This column compares SOC across years.

¶ Pea vines = (2.24 Mg ha^{-1} field weight; 87.8% dry matter; 0.82 Mg C ha^{-1} and 0.037 Mg N ha^{-1}; applied 1–3 d before plowing.

\# Manure = (22.4 Mg ha^{-1} wet wt; 47.5% dry matter; 1.69 Mg C ha^{-1} and 0.14 Mg N ha^{-1}; applied 1–3 d before plowing in April or May of plow year.

†† ns = not significant.

Table 6. Fertilizer effects on biomass, grain yield (1989–2003), and soil organic carbon (SOC) (1984–2005). tillage fertility LTE (winter wheat-summer fallow).

N†	TDM†	GYD†	SDM†	Organic C‡			Significance level§
	1989–2003			1984	1995	2005	
kg ha^{-1}	—— Mg ha^{-1} yr^{-1} ——			——— Mg ha^{-1} ———			
0	5.0d	1.9c	3.4d	–	62.8a	55.4a	***
45	6.2c	2.6b	4.2c	66.9a	63.3a	56.5a	***
90	6.7b	2.8a	4.4b	63.9a	61.9a	56.4a	***
135	6.9ab	2.8a	4.6a	64.9a	63.4a	56.0a	***
180	7.1a	2.9a	4.8a	66.1a	62.6a	55.5a	***
se	0.09	0.04	0.08	1.4	1.1	1.2	

* Indicates that SOC means in 1995 and 2005 for the 0 N treatment and in 1984 and 2005 for the other N treatments (45–180) are significantly different at the 0.05 probability level.

*** Indicates that SOC means in 1995 and 2005 for the 0 N treatment and in 1984 and 2005 for the other N treatments (45–180) are significantly different at the 0.001 probability level.

† N, nitrogen; TDM, total bundle dry matter; GYD, combine grain yield; SDM, bundle straw yield, SOC, soil organic carbon.

‡ Within columns, means followed by the same letter are not significantly different according to LSD (0.05)

§ This column compares SOC across years.

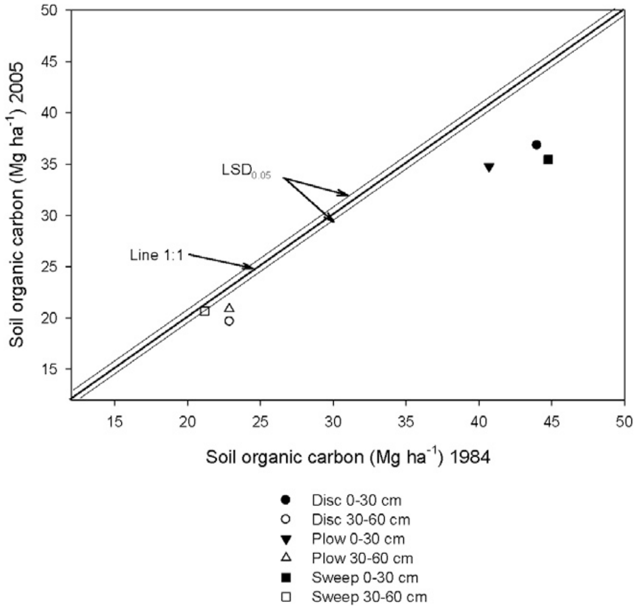

Fig. 2. Tillage and fertility effects on soil organic carbon changes in the tillage fertility long-term experiment from 1984 to 2005 at the Oregon State University, Columbia Basin Agricultural Research Center, Pendleton, OR.

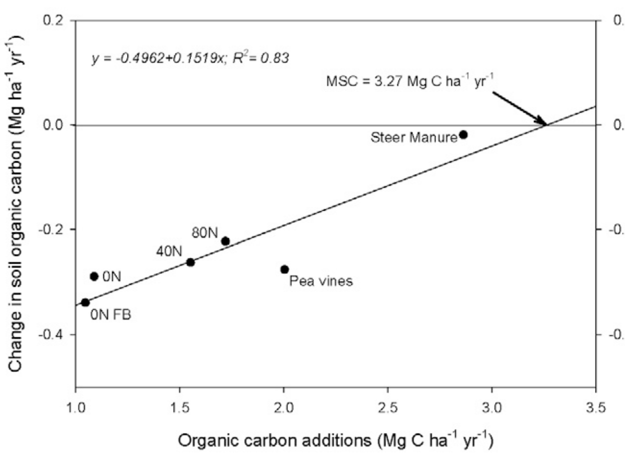

Fig. 3. Changes in soil organic carbon (SOC) as influenced by straw biomass produced from N, pea vines, and steer manure additions and straw burning from 1976 to 2005 in the crop residue long-term experiment under the conventional winter wheat-summer fallow using plow cultivation at the Oregon State University, Columbia Basin Agricultural Research Center, Pendleton, OR. MSC: minimum amount of carbon additions required to maintain SOC.

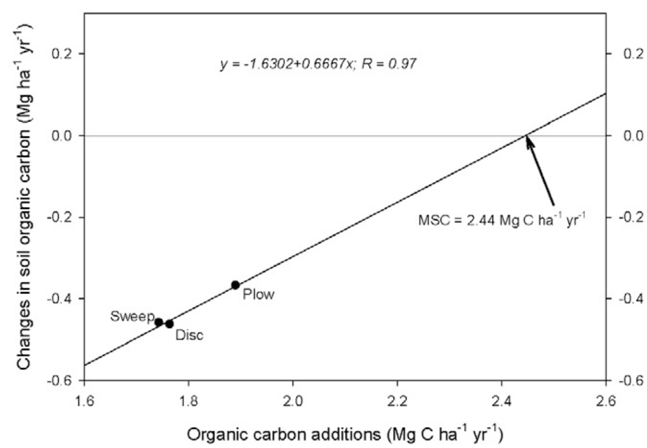

Fig. 4. Changes in soil organic carbon (SOC) as influenced by straw biomass produced under the winter wheat summer fallow cropping system using Plow, Disc, and Sweep cultivation from 1984 to 2005 in the Tillage Fertility (TF) long-term experiment at the Oregon State University, Columbia Basin Agricultural Research Center, Pendleton, OR. MSC: minimum amount of carbon additions required to maintain SOC.

growing of one crop in 2 yr that produced insufficient biomass to maintain SOC. Even converting WW-SF under CT to WW-SF under NT showed no significant increase in SOC (West and Post, 2002) for the same reason. Using data from 1976 to 2005 it was estimated that additions of 3.3 Mg C ha^{-1} yr^{-1} or 7.8 Mg ha^{-1} yr^{-1} of straw biomass was required to maintain SOC at the 1976 SOC level in the CR-LTE, a WW-SF cropping system (Fig. 3). In the TF-LTE, another WW-SF cropping system, data from 1984 to 2005 revealed that additions of 2.4 Mg C ha^{-1} yr^{-1}or 5.8 Mg ha^{-1} yr^{-1} of straw biomass were required to maintain SOC at the 1984 SOC level (Fig. 4). The MSB in the TF-LTE was similar to the MSB of 5 to 5.5 Mg ha^{-1} yr^{-1} estimated for the 1931 to 1986 period in the same experiment (Rasmussen et al., 1980; Rasmussen and Smiley, 1997) and other MSBs estimated for other crops (Larson et al., 1972; Johnson et al., 2006). In the CR-LTE, the MSB estimated for the 1976 to 2005 period was higher than the MSB for the same experiment before 1986. With continued SOC loss under this WW-SF system, it is expected that the MSB would increase overtime. The MSB for the CR-LTE was higher than the MSB for TF-LTE probably reflecting the differences in SOC content of the two experiments. More SOC has been lost in the CR-LTE that was initiated in 1931 than in TF-LTE initiated in 1964. Obviously the actual MSB for both experiments should be higher than the estimated values if belowground biomass was considered (Wilts

Table 7. Tillage effects on biomass, grain yield (1989–2003), and soil organic carbon (SOC) (1984–2005) in the tillage fertility LTE (winter wheat–summer fallow).

Tillage	TDM†	GYD†	SDM†	SOC‡			Significant level§	Residue cover at seeding %
	1989–2003			1984	1995	2005		2004–2005
	Mg ha^{-1} yr^{-1}			Mg ha^{-1}				
Plow	6.8a	2.8a	4.5a	63.5a	61.3b	55.4a	***	22b
Disc	6.3b	2.6b	4.2b	66.9a	65.2a	56.7a	***	63a
Sweep	6.2b	2.5b	4.2b	65.9a	62.0b	55.8a	***	66a
se	0.07	0.03	0.05	1.2	0.9	0.9	***	3.5

* Indicates that SOC means in 1984 and 2005 are significantly different at the 0.05 probability level.

*** Indicates that SOC means in 1984 and 2005 are significantly different at the 0.001 probability level.

† TDM, total bundle dry matter; GYD, combine grain yield; SDM, bundle straw yield, SOC, soil organic carbon.

‡ Within columns, means followed by the same letter are not significantly different according to LSD (0.05)

§ This column compares SOC across years.

et al., 2004; Johnson et al., 2006). Unfortunately no consistent belowground biomass data are available at the Pendleton LTEs. Both the CR-LTE and the TF-LTE produced less biomass than the estimated MSBs, a situation that has led to the depletion of SOC in the WW-SF cropping systems of the PNW. Only the manure treatment which added 0.85 Mg C ha^{-1} yr^{-1} and 2.02 Mg C ha^{-1} yr^{-1} from straw biomass (4.8 Mg ha^{-1} yr^{-1}) maintained SOC. The continuous decline of SOC will, in the long-run, negatively impact the physical, chemical, and hydrological properties of the 1.5 million ha of soils under WW-SF fallow rotation in the PNW. To this end harvesting crop residues from WW-SF systems of the PNW for biofuel production would exacerbate the depletion of SOC from these soils leading to negative impacts on soil productivity and crop productivity in the long term.

Continuous Annual Cropping

With annual cropping, crop residues were added every year resulting in different SOC dynamics compared to the WW-SF cropping systems. In the WP-LTE, SOC level in the 0- to 30-cm depth profile observed in 1995 was significantly reduced in the SP treatment, maintained in the MT and FP treatments, and significantly increased in the NT treatment (Fig. 5). In the 30 to 60 depth profile, all treatments increased SOC that was observed in 1995 with NT showing the greatest increase. When the 0- to 60-cm profile was considered, all treatments had statistically similar SOC levels in 1995 (Table 8). In 2005, however, all tillage practices had increased total SOC in the 0- to 60-cm depth profile, and this was significantly so under the NT practice (Table 8). No-till increased SOC at the rate of 0.89 Mg ha^{-1} yr^{-1} or by 13.8% in 10 yr compared to 0.10, 0.11, 0.02 Mg ha^{-1} yr^{-1} or by 1.5, 1.7, 0.3% in the MT, FP, and SP treatment in 10 yr, respectively. However, the average yearly aboveground total and straw biomass from 1995 to 2004 was not significantly different among all treatments (Table 8). If the aboveground biomass was the same then the degree of residue incorporation and belowground biomass may explain the differences in SOC. There was significantly more residue cover under NT than under the other treatments (Table 8). Based on the relationship between surface residue cover and flat biomass (McCool et al., 1995; Steiner et al., 2000) it is reasonable to assume that more crop residues were incorporated under the FP, SP, and MT treatments that used CT methods than under NT treatments. Indeed plowing has

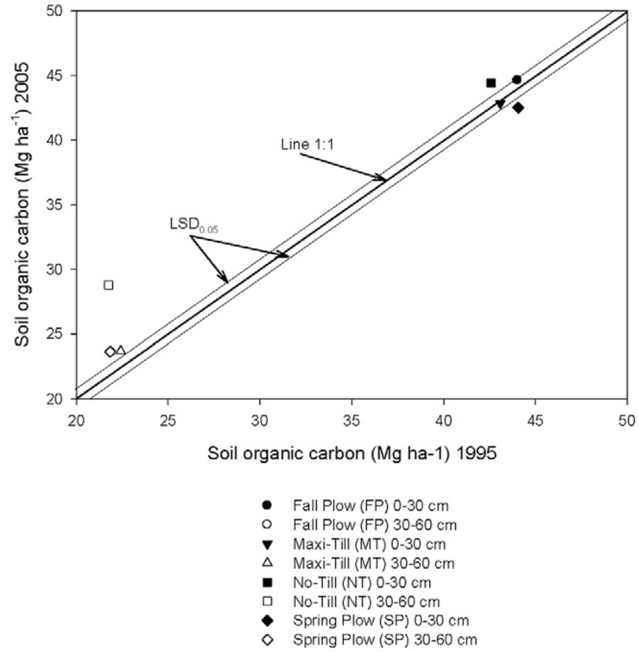

Fig. 5. Tillage effects on soil organic carbon changes in the wheat-pea long-term experiment from 1995 to 2005 at the Oregon State University, Columbia Basin Agricultural Research Center, Pendleton, OR.

been shown to bury most residues and to exacerbate SOC loss compared to disking, chiseling, and NT (Reicosky et al., 1995). Based on these results SOC was maintained or increased when cropping intensity was increased and tillage eliminated. Collins et al. (1992), working on the same LTEs, reached the same conclusion. However, their estimates of SOC additions were lower than rates observed in this study particularly under NT. They estimated SOC in the top 20 cm while our present study used the top 60 cm. Furthermore, when their study was conducted (1987), the NT treatments had not been introduced in this experiment.

Based on this study, there may be potential for harvesting residues for biofuel production under the WP-LTE annual cropping systems but only when straw biomass requirements for conservation purposes are exceeded. Using data from 1995 to 2005 it was estimated that additions of 2.2 Mg C ha^{-1} yr^{-1} or 5.2 Mg ha^{-1} yr^{-1} of straw biomass were required to maintain SOC at the 1995 SOC level in the WP-LTE (Fig. 6). All treatments in the WP-LTE

Table 8. Tillage effects on biomass, grain yield (1995–2004, wheat and pea combined), and soil organic carbon (SOC) (1995–2005) in the wheat-pea rotation long-term experiement (Continuous annual cropping).

Tillage	TDM†	GYD†	SDM†	SOC‡		Significant level§	Residue cover at seeding %
	1995–2004			1995	2005		2005
	Mg ha^{-1} yr^{-1}			Mg ha^{-1}			
Maxi-till (MT)	9.0a	4.0ab	5.1a	65.5a	66.5b	ns¶	49b
Fall plow (FP)	9.1a	4.0ab	5.2a	65.9a	68.2b	ns	27c
Spring plow (SP)	9.2a	4.1a	5.2a	65.9a	66.1b	ns	21c
No-till (NT)	9.0a	3.8b	5.2a	64.3a	73.2a	***	97a
se	0.08	0.02	0.06	1.1	1.5		4.1

* Indicates that SOC means in 1995 and 2005 are significantly different at the 0.05 probability level.
** Indicates that SOC means in 1995 and 2005 are significantly different at the 0.01 probability level.
*** Indicates that SOC means in 1995 and 2005 are significantly different at the 0.001 probability level.
† N, nitrogen; TDM, total bundle dry matter; GYD, combine grain yield; SDM, bundle straw yield, SOC, soil organic carbon.
‡ Within columns, means followed by the same letter are not significantly different according to LSD (0.05)
§ This column compares SOC across years.
¶ ns = not significant.

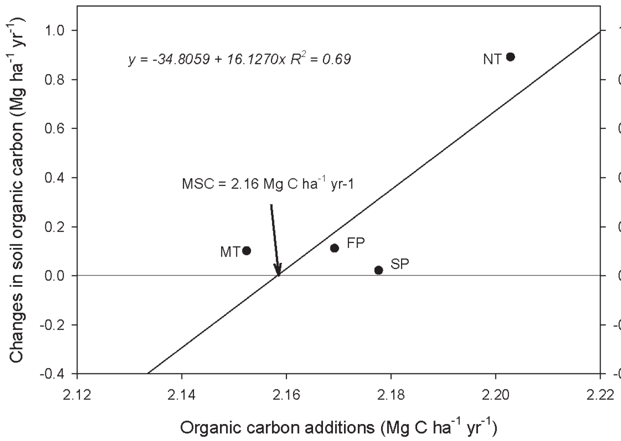

Fig. 6. Changes in soil organic carbon (SOC) as influenced by straw biomass produced under the continuous winter wheat-spring pea rotation long-term experiment using maxi-till (MT), fall plow (FP), spring plow (SP), and no-till (NT) cropping system from 1995 to 2005 at the Oregon State University, Columbia Basin Agricultural Research Center, Pendleton, OR. MSC: minimum amount of carbon additions required to maintain SOC.

produced more straw biomass than the required MSB based on 1995 SOC levels. However, given that most agricultural land, including the PNW, has lost more than half the original native praire SOC (Huggins et al., 1998; Lal et al., 1998), our priority should emphasize retaining straw residues for SOC build-up and conservation purposes and not for biofuel production.

CONCLUSIONS

Based on these results WW-SF, the predominant cropping system in the PNW depleted SOC. This was mainly attributed to insufficient C input. Growing one crop in 2 yr did not produce enough crop biomass to maintain or buildup SOC. Removal of crop residues for biofuel production will likely exacerbate SOC depletion and in the long term reduce soil and crop productivity. Crop intensification through continuous annual cropping, on the other hand, maintained or increased SOC. There may be a possibility of harvesting some biomass for biofuel production under NT continuous annual cropping systems if MSB and conservation requirements are exceeded. The period of record for the Pendleton LTEs involving continuous annual NT cropping does not extend as far back as the CT system and more time is needed to determine if the NT system continues to build-up SOC over time. Continuous annual NT cropping is a starting point, however, to maintain or increase SOC. Research to find ways to increase SOC using crops that produce more aboveground and belowground biomass and available soil amendments, should be conducted not only for biofuel purposes but primarily to maintain or increase SOC in the WW-SF cropping systems of the PNW.

ACKNOWLEDGMENTS

The authors would like to thank the Oregon State University CBARC and the Columbia Plateau Conservation Research Center at Pendleton, OR for supporting the Pendleton LTEs and Karl Rhinhart for maintaining the LTEs and for assistance in data collection.

REFERENCES

Banowetz, G.M., A. Boateng, J.J. Steiner, S.M. Griffith, V. Sethi, and H. El-Nashaar. 2007. Assessment of straw biomass feedstock resources in Pacific Northwest. Biomass Bioenergy 32:629–634.

Blanco-Canqui, H. 2010. Energy crops and their implications on soil and environment. Agron. J. 102:402–419.

Blanco-Canqui, H., and R. Lal. 2009a. Crop residue removal impacts on soil productivity and environmental quality. Crit. Rev. Plant Sci. 28:139–163.

Blanco-Canqui, H., and R. Lal. 2009b. Corn stover removal for expanded uses reduces soil fertility and structural stability. Soil Sci. Soc. Am. J. 73:418–426.

Collins, H.P., P.E. Rasmussen, and C.L. Douglas. 1992. Crop rotation and residue management effects on soil carbon and microbial dynamics. Soil Sci. Soc. Am. J. 56:783–788.

Franzluebbers, A.J. 2004. Tillage and residue management effects on soil organic matter. p. 227–268. *In* F. Magdoff and R.R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press, New York.

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

Johnson, J.M.-F., R.R. Allmaras, and D.C. Reicosky. 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. Agron. J. 98:622–636.

Laften, J.M., M. Amemiya, and E.A. Hintz. 1981. Measuring crop residue cover. J. Soil Water Conserv. Nov.-Dec.:341–343.

Lafond, G.P., M. Stumborg, R. Lemke, W.E. May, C.B. Holzapfel, and C.A. Campbell. 2009. Quantifying straw removal through baling and measuring the long-term impact on soil quality and wheat production. Agron. J. 101:529–537.

Lal, R. 2007. Biofuels from crop residues. Soil Tillage Res. 93:237–238.

Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. 1998. Potential of US cropland to sequester carbon and mitigate the greenhouse effect. Sleeping Bear Press, Chelsea, MI.

Larson, W.E., C.E. Clapp, W.H. Pierre, and Y.B. Morachan. 1972. Effects of increasing amounts of organic residues on continuous corn: II. Organic carbon, nitrogen, phosphorus and sulfur. Agron. J. 64:204–208.

Lindstrom, M.J. 1986. Effects of residue harvesting on water runoff, soil-erosion and nutrient loss. Agric. Ecosyst. Environ. 16:103–112.

Machado, S., S. Petrie, K. Rhinhart, and R.E. Ramig. 2008. Tillage effects on water use and grain yield of winter wheat and green pea in rotation. Agron. J. 100:154–162.

Machado, S., K. Rhinhart, and S. Petrie. 2006. Long-term cropping systems effects on soil organic carbon sequestration in eastern Oregon. J. Environ. Qual. 35:1548–1553.

Malhi, S.S., and H.R. Kutcher. 2007. Small grains stubble burning and tillage effects on soil organic C and N, and aggregation in northern Saskatchewan. Soil Tillage Res. 94:353–361.

Mann, L., V. Tolbert, and J. Cushman. 2002. Potential environmental effects of corn (*Zea mays* L.) stover removal with emphasis on soil organic matter and erosion. Agric. Ecosyst. Environ. 89:149–166.

McCool, D.K., R.I. Papendick, J.E. Hammel. 1995. Surface residue management. p. 10–16. *In* R.I. Papendick and W.C. Moldenhauer (ed.) Crop residue management to reduce erosion and improve soil quality. Conserv. Rep. no. 40. USDA Agric. Res. Serv., Washington, DC.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon and organic matter. p. 534–580. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Rasmussen, P.E., R.R. Allmaras, C.R. Rohde, and N.C. Roager, Jr. 1980. Crop residue influences on soil carbon and nitrogen in a wheat fallow system. Soil Sci. Soc. Am. J. 44:596–600.

Rasmussen, P.E., S.L. Albrecht, and R.W. Smiley. 1998. Soil C and N changes under tillage and cropping systems in semi-arid Pacific Northwest agriculture. Soil Tillage Res. 47:197–205.

Rasmussen, P.E., and H.P. Collins. 1991. Long-term impacts of tillage, fertilizer, and crop residue on soil organic matter in temperate semi-arid regions. Adv. Agron. 45:93–134.

Rasmussen, P.E., and W.J. Parton. 1994. Long-term effects of residue management in wheat/fallow. I. Inputs, yield, soil organic matter. Soil Sci. Soc. Am. J. 58:523–530.

Rasmussen, P.E., and R.W. Smiley. 1997. Soil carbon and nitrogen change in long-term agricultural experiments at Pendleton, Oregon. p. 353–360. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems—Long-term experiments in North America. CRC Press, New York.

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

SAS Institute. 2003. SAS/STAT user's guide. Version 9.1. SAS Inst., Cary, NC.

Steiner, J.L., H.H. Schomberg, P.W. Unger, and J. Cresap. 2000. Biomass and residue cover relationships of fresh and decomposing small grain residue. Soil Sci. Soc. Am. J. 64:2109–2114.

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

Wilhelm, W.W., J.M.F. Johnson, D.L. Karlen, and D.T. Lightle. 2007. Corn stover to sustain soil organic carbon further constrains biomass supply. Agron. J. 99:1665–1667.

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