Soil & Crop Management

Crop Management Effects on Crop Residue Production and Changes in Soil Organic Carbon in the Central Great Plains

Joseph G. Benjamin,* Ardell D. Halvorson, David Christopher Nielsen, and Maysoon M. Mikha

ABSTRACT

Crop biomass has been proposed as a source stock for bioethanol production. Levels of crop residue removal must be determined to prevent degradation of soil physical and chemical properties resulting from soil organic carbon (SOC) loss. Carbon inputs from crop residues and an estimate of inputs from roots and rhizodeposition (C_{return}) were calculated and compared with changes in SOC after seven cropping seasons at Akron, CO. Tillage treatments included a chisel plow (CP) and a no-till (NT) treatment. A crop rotation alternating grasses and broadleaf crops was compared with continuous corn (*Zea mays* L.). Irrigation treatments included water application to meet evapotranspiration demand or application only during the reproductive stage of each crop. Total C_{return} varied from 25 Mg ha^{-1} for the delayed irrigation, crop rotation plots to 63 Mg ha^{-1} for the fully irrigated, continuous corn plots. The change in SOC in the surface 30 cm of soil varied from −0.8 Mg SOC ha^{-1} for the rotation plots to a gain of 2.8 Mg ha^{-1} for the continuous corn plots after 7 yr. Correlating crop residue input with change in SOC showed that about 4.6 Mg ha^{-1} yr^{-1} C_{return} is needed to maintain SOC levels for NT cropping systems and an average of 7.4 Mg ha^{-1} yr^{-1} C_{return} is needed to maintain SOC levels under chisel tillage. Continuous corn was the only system that consistently provided sufficient crop residue to maintain SOC levels. Residue removal for off-farm use should consider only amounts that can be harvested without decreasing SOC levels.

There are increasingly competitive pressures to make use of crop residues that remain after the harvest of grain in many agricultural crops. High energy prices and the projected shortage of fossil fuels over the next 50 yr have led to interest in replacing some of the fossil fuel energy needs with renewable biofuels. The amounts of crop residue and waste products from agricultural processing are large. Kim and Dale (2004) estimated that potential global bioethanol production could replace up to 33% of global gasoline consumption. Corn crop residue has been proposed as a source stock for biofuel production in North America, potentially providing 38.4 GL yr^{-1} of ethanol. Crop residues are one component of a biofuels policy that also includes perennial plants grown for energy production, forest residues, and municipal and industrial wastes (Tilman et al., 2009).

The use of crop residues and crop waste for energy production removes the use of these products for maintaining soil organic matter. Soil organic carbon is considered a key component in removing CO_2 from the atmosphere to decrease greenhouse gas emissions and mitigate global climate change (Christopher et al., 2009). Benefits of increasing SOC include sequestering atmospheric CO_2 as well as improving soil physical, chemical, and biological properties of soils. Lal (2009) discourages the use of crop residues for energy production. He cites several reasons to return crop residues to the field including: (i) recycling plant nutrients, (ii) carbon sequestration, (iii) improving soil physical properties such as soil structure and water retention and transmission, (iv) enhancing soil fauna, (v) improving water infiltration, (vi) controlling water runoff, (vii) conserving water in the root zone, and (viii) sustaining agronomic productivity.

The effectiveness of increasing SOC in soil by changing cropping and tillage systems appears to vary among different regions in the United States. In a study conducted in Indiana, Ohio, and Pennsylvania Christopher et al. (2009) reported that in some soils, NT increased SOC while in other soils conventional management increased SOC. Reasons for the mixed results were not apparent. In the central Great Plains, studies have shown that NT systems increased SOC more than tilled systems (Six et al., 1999, 2000; Mikha and Rice, 2004), but these studies generally examined the change in SOC in the 0 to 5 or 0 to15 cm soil depths. McVay et al. (2006), for instance, showed a greater increase in SOC in the 0 to 5 cm depth for NT than sweep tillage, but no differences in when averaged over the 0 to 15 cm depth.

The contribution of the crop root system to formation and increase of SOC is important when considering the selection of a crop rotation in a cropping system. Barber (1979) estimated that 8 to 11% of corn stalk residue was transformed into SOC while at least 18% of corn roots was transformed into SOC. Allmaras et al. (2004) showed that measurement of the quantity of plant roots alone underestimates the roll of roots in formation of SOC. They

J.G. Benjamin, D.C. Nielsen, and M.M. Mikha, Central Great Plains Research Station, 40335 Co. Rd. GG, Akron, CO 80720; A.D. Halvorson, USDA-ARS, 2150 Centre Ave, Bldg. D, Ste. 100, Fort Collins, CO 80526-8119. Received 23 Nov. 2009. Corresponding author (Joseph.Benjamin@ars.usda.gov).

Published in Agron. J. 102:990–997 (2010)
Published online 29 Mar., 2010
doi:10.2134/agronj2009.0483

AGRONOMY JOURNAL since 1908

Abbreviations: CC, continuous corn; C_{grain}, carbon content of the grain; C_{res}, carbon content of the crop residue; C_{return}, carbon returned, C_{root}, root and rhizodeposition carbon, CP, chisel plow; NT, no-till system; Rot, rotation; SIC, soil inorganic carbon; SOC, soil organic carbon; TSC, total soil carbon.

Table 1. Details of cropping history for rotations, 2001 to 2007.

Year	Rotation†	Crop	Variety	Row spacing	Population	N–P–K–Zn
				m	seeds ha^{-1}	kg ha^{-1}
2001	CC	corn	Dekalb DK 493	0.8	80,000	160–22–0–0
	Rot	bean	Red Kidney	0.8	250,000	45–22–0–0
2002	CC	corn	Dekalb DK 493	0.8	80,000	160–22–0–0
	Rot	barley	Coors C56	0.18	41 kg ha^{-1}	68–34–0–0
2003	CC	corn	NK N42-B7	0.8	86,000	215–22–0–0
	Rot	sunflower	Triumph 567	0.8	70,000	34–22–0–0
2004	CC	corn	Laser L62-C2	0.8	86,000	215–22–0–0.6
	Rot	corn	Laser L62-C2	0.8	86,000	215–22–0–0.6
2005	CC	corn	N65-C5	0.8	86,000	215–22–0–0.6
	Rot	pea	Arvika	0.18	1.4 × 10^{6}	18–34–0–0
2006	CC	corn	NK N70-C7RR	0.8	86,000	215–22–0–0.6
	Rot	wheat	Jaguleene	0.18	41 kg ha^{-1}	68–34–0–0
2007	CC	corn	NK N51-C1	0.8	86,000	215–22–0–0.6
	Rot	sunfower	Triumph 567	0.8	70,000	34–22–0–0

† Abbreviations for rotation include continuous corn (CC) and crop rotation (Rot).

noted that rhizodeposition in the field is a large contributor to the total C cycle and must be included in the analysis at the field level. Johnson et al. (2006) summarized the contributions of different plant parts from different plant species to SOC and gave guidelines for including the contributions of plant roots and rhizodeposition to the total C cycle when analyzing changes in SOC.

Under dryland conditions in the central Great Plains of the United States increasing cropping intensity has potential for increasing SOC stocks due to increased residue inputs (Peterson et al., 1998; Halvorson et al., 1999; Benjamin et al., 2008). It is expected that, under irrigation, an even greater increase in SOC could be attained because of the greater productivity of irrigated systems compared with dryland systems in this climate (Halvorson et al., 2009; Halvorson and Johnson, 2009). However, irrigation may also increase C mineralization, leading to no net gain in sequestered C.

The objectives of this study were to determine: (i) changes in SOC with varying levels of C additions from crop residues and root biomass and (ii) the level of crop residue removal that could be sustained without loss of SOC from the soil.

MATERIALS AND METHODS

The study was conducted at the USDA-ARS Central Great Plains Research Station near Akron, CO (40°8′ N, 103°9′ W, elevation 1384 m). The research station location is within a semiarid climate with approximately 40 cm mean annual precipitation. The soil is a Weld silt loam (fine, smectitic, mesic Aridic Argiustolls). This soil has a silt loam Ap horizon from about 0 to 12 cm with fine granular structure. A silty clay loam Bt1 horizon with fine to medium subangular blocky structure extends from about 12 to 24 cm with a smooth boundary to a silty clay loam Bt2 horizon, also with fine to medium subangular blocky structure to about 41 cm. A silty clay loam Btk horizon with fine to medium subangular blocky structure extends to about 64 cm.

The irrigation-tillage-crop rotation experiment started in 2001. The experiment was organized as a split-plot design with three replications. Plots were 18 by 9 m. The main plot was an irrigation treatment of either full or delayed irrigation. In the full irrigation treatment irrigation water was applied weekly with a lateral move irrigation system. Irrigation rates were based on calculated crop specific evapotranspiration demands (ET) (Allen, 2000; Allen et al., 1998; Nielsen and Hinkle, 1996; Jensen et al., 1990). Credit was given for any rainfall that week. In the delayed irrigation treatment, water was not applied during the crop's vegetative growth stages. During reproductive stages, water was applied at the calculated rate for the fully irrigated plots. Due to dry overall soil conditions in 2004, all plots were fully irrigated.

Crop rotation and tillage subplots were randomized within the main irrigation plots. A NT consisted of directly planting into the previous crop residues. A CP system consisted of a fall CP operation 0.35 m deep with a parabolic-shank deep ripper. The shanks on the ripper had 0.6-m centers. The tillage was followed in the spring by one or two passes with a mulch treader to break up clods and smooth the soil surface in preparation for planting. Depth of operation of the mulch treader was approximately 50 mm. Two crop rotations were used in a factorial arrangement with tillage. One rotation (CC) consisted of continuous corn production. The other rotation (Rot) consisted of a variety of crops, alternating broadleaf and grass species, with the potential to use less irrigation water than corn. Rotation plots grew red kidney bean (*Phaseolus vulgaris* L.) in 2001, spring barley (*Hordeum vulgare* L.) in 2002, sunflower (*Helianthus annuus* L.) in 2003, corn in 2004, spring pea (*Pisum sativum* L.) in 2005, winter wheat (*Triticum aestivum* L.) in 2006, and sunflower in 2007. Details of the cropping history and management are shown in Table 1. Previous cropping history on the plot area was continuous corn production under irrigation since at least 1997. No controlled machinery traffic pattern was imposed previously. For this experiment plot size and machinery working widths was such that the wheel tracks for field operations followed a controlled wheel traffic pattern.

Soil samples were collected in the spring of 2001 in non-tracked areas before planting for SOC analysis. Samples were collected using a 5 cm diam. probe on a Giddings[1] hydraulic soil sampler (Giddings Machine Co., Windsor, CO) from the 0 to15 and 15 to 30 cm depths. Three subsamples per plot were composited for the main sample. Separate samples were collected for bulk density (ρ_b) determination using the Giddings

[1] Mention of specific brand names are for informational purposes only and do not denote an endorsement of that brand over other, similar brands.

Table 2. Rainfall and irrigation for the growing season of crops in this study

Year	Crop	Irrigation treatment	Rainfall	Irrigation	Total
			cm		
2001	corn	full	32.2	32.3	64.5
		delayed	32.2	17.8	50.0
	red kidney bean	full	32.2	32.3	64.5
		delayed	32.2	17.8	50.0
2002	corn	full	18.3	35.8	54.1
		delayed	18.3	28.4	46.7
	spring barley	full	8.4	27.4	35.8
		delayed	8.4	24.4	32.8
2003	corn	full	34.5	37.8	72.3
		delayed	34.5	28.7	63.2
	sunflower	full	34.5	37.8	72.3
		delayed	34.5	28.7	63.2
2004	corn	full	32.5	38.1	70.6
		delayed	32.5	38.1	70.6
	corn	full	32.5	38.1	70.6
		delayed	32.5	38.1	70.6
2005	corn	full	39.6	28.6	68.2
		delayed	39.6	16.5	56.1
	field pea	full	19.8	13.3	33.1
		delayed	19.8	7.6	27.4
2006	corn	full	26.7	44.5	71.2
		delayed	26.7	23.5	50.2
	winter wheat	full	20.6	21.6	42.2
		delayed	20.6	12.7	33.3
2007	corn	full	24.4	36.8	61.2
		delayed	24.4	22.9	47.3
	sunflower	full	24.4	36.8	61.2
		delayed	24.4	22.9	47.3

hydraulic sampler and a probe that used 7.5 diam. by 7.5 deep aluminum rings to confine the undisturbed soil sample.

Soil samples for SOC determination were prescreened through a 2-mm sieve to remove large pieces of plant material before further grinding with a flail type soil grinder to pass through a 2-mm screen. Soil samples collected for SOC analysis were ground to pass a 150-μ screen on a roller table and analyzed total soil carbon (TSC) concentration using a Carlo Erba C-N analyzer (Haake Buchler Instruments, Inc., Saddle Brook, NJ). Soil inorganic carbon (SIC) concentration was determined using the method of Sherrod et al. (2002). Soil organic C concentration was the difference between TSC and SIC.

The same sampling procedure used in 2001 for SOC and ρ_b was used in the spring of 2008 before planting. SOC was determined with a Carlo Erba C-N analyzer at a commercial lab (Ward Laboratories, Kearney, NE).

The SOC_{mass} (Mg ha^{-1}) (volumetric basis) in the 0 to 15 cm and 15 to 30 cm soil layers was determined by:

$$SOC_{mass} = d\, \rho_b\, SOC\, 10^{-1} \qquad [1]$$

where d is the soil depth increment (cm), ρ_b is the soil bulk density (Mg m^{-3}) and SOC is the concentration of SOC (g kg^{-1}) in this depth.

Each year the aboveground crop residue remaining after harvest was measured. For dry bean, field pea, spring barley, and winter wheat a 1 m^2 area was selected randomly in the plot area shortly before harvest. The plants in the area were clipped at ground level, placed in mesh bags and allowed to air dry. The grain was threshed from the sample and the grain and crop residue weights determined. A subsample of the crop residue was oven dried at 70°C for 24 h to determine water content. Crop residue yields were expressed on an oven dry basis.

For corn and sunflower, four typical plants were selected from each plot. The plants were clipped at ground level, placed in mesh bags and allowed to dry. The grain was shelled from the cob or head and the grain and crop residue weights determined. A subsample of the crop residue was oven dried at 70°C for 24 h to determine water content. Crop residue weight per plant, adjusted to an oven-dry basis, and measured plant population at harvest were used to calculate crop residue yield.

Estimation of the C content in the grain and crop residues produced on each plot used guidelines provided by Johnson et al. (2006). The carbon content of the grain (C_{grain}) was calculated by

$$C_{grain} = 0.4 \text{ grain} \qquad [2]$$

where grain is the mass of harvested grain. The carbon content of the crop residue (C_{res}) was calculated by

$$C_{root} = 0.4 \text{ residue} \qquad [3]$$

where residue is the mass of residue left in the field.

An estimate of the belowground root and rhizodeposition carbon (C_{root}) produced each year was calculated from the mass of aboveground plant material using guidelines provided by Johnson et al. (2006)

$$C_{root} = k_{rec}\,(C_{grain} + C_{root}) \qquad [4]$$

where k_{rec} is 0.6 for corn, barley, wheat, pea, and dry bean and 0.25 for sunflower. The total carbon returned (C_{return}) to the soil was calculated by

$$C_{return} = C_{res} + C_{root} \qquad [5]$$

Analyses of variance were conducted to determine irrigation timing, crop rotation, and tillage effects on crop residue production and SOC. A protected LSD test was used to determine treatment differences. The LSD was used to distinguish treatment effects only if the F test was significant at the 0.05 probability level.

RESULTS

The growth cycle of bean (2001) and sunflower (2003, 2007) were similar enough to corn that irrigation timing was the same for corn and these crops (Table 2). The total water (irrigation and rainfall) applied to corn under the full irrigation schedule varied between 54.1 and 72.3 cm. Under delayed irrigation scheduling, total water was between 46.7 and 63.2 cm. Spring barley, field pea, and winter wheat had earlier plantings and shorter growing seasons than corn so less water was applied to these crops and less rainfall occurred during their life cycles. The total amount of water available for these crops under full irrigation varied between

Table 3. Carbon content of grain (C_{grain}) from spring 2001 to spring 2008.

Irrigation	Tillage†	Rotation‡	Year							Total
			2001	2002	2003	2004	2005	2006	2007	
			Mg ha^{-1}							
Full	NT	CC	3.54	1.70	4.16	3.82	2.09	5.17	4.35	24.83
Full	CP	CC	3.77	2.06	4.46	3.95	2.08	4.80	4.26	25.37
Delayed	NT	CC	3.63	1.34	2.30	3.66	2.29	2.32	3.19	18.74
Delayed	CP	CC	3.29	0.95	2.70	2.56	3.14	2.43	2.84	17.92
Full	NT	Rot	0.97	2.22	1.73	3.34	1.18	1.29	0.91	11.64
Full	CP	Rot	1.08	2.11	1.58	2.70	0.20	1.12	0.79	9.58
Delayed	NT	Rot	1.03	1.92	1.87	2.11	0.40	0.99	0.95	9.28
Delayed	CP	Rot	0.88	1.84	1.64	1.67	0.33	0.80	0.81	7.96
Source§	$P > f$									
Irrigation (I)			0.52	0.0038	0.088	0.15	0.22	0.011	0.15	0.047
Rotation (*R*)			<0.0001	0.001	<0.0001	0.0015	<0.0001	<0.0001	<0.0001	<0.0001
Tillage (T)			0.77	0.63	0.22	0.12	0.71	0.61	0.24	0.28
I × R			0.57	0.099	0.024	0.81	0.32	0.0064	0.093	0.036
I × T			0.27	0.12	0.66	0.70	0.19	0.95	0.74	0.96
R × T			0.91	0.83	0.03	0.99	0.21	0.99	0.42	0.37
I × R × T			0.48	0.10	0.69	0.24	0.68	0.70	0.96	0.57

† Tillage systems include no till (NT) and chisel plow (CP).

‡ Rotations include continuous corn (CC) and mixed grass-broadleaf species (Rot).

§ The test for significance of irrigation effects on Cgrain used the irrigation × rep interaction for the error term, crop × irrigation effects were tested using the irrigation by crop × rep interaction for the error term, and tillage × irrigation effects were tested using the irrigation ´ tillage ´ rep interaction for the error term.

33.1 cm for field pea and 42.2 cm for winter wheat. Because of spring rainfall and cool spring temperatures, the ET demand for barley (2002) and field pea (2005) was low and only one or two additional irrigations were needed for the fully irrigated plots compared with the delayed irrigation plots. Winter wheat (2006) required more irrigation applications during vegetative growth than either barley or pea to fully irrigate the plots. The total amount of water available to barley, field pea, and winter wheat under delayed irrigation varied between 27.4 and 35.8 cm.

Irrigation amounts had a significant effect on C_{grain} production over the seven crop years in this study (Table 3). The fully irrigated plots produced 17.9 Mg ha^{-1} C_{grain} when averaged over rotation and tillage system compared with 13.7 Mg ha^{-1} C_{grain} for the delayed irrigation system. Rotation had a larger effect on the amount of C_{grain} produced. The CC plots, averaged over irrigation and tillage treatments, produced 21.8 Mg ha^{-1} of C_{grain} during the seven crop years compared with only 9.7 Mg ha^{-1} C_{grain} for Rot plots. Rotation had a significant effect on C_{grain} every year. There was a significant interaction between crop rotation and irrigation amounts. The fully irrigated CC plots produced 25.1 Mg ha^{-1} of C_{grain} while the delayed irrigation CC plots produced 18.5 Mg ha^{-1} of C_{grain}, a decline of 26%. The fully irrigated Rot plots produced 10.5 Mg ha^{-1} of C_{grain} compared with 8.8 Mg ha^{-1} of C_{grain} for the delayed irrigated plots, a decline of 16%. There was no significant tillage, rotation × tillage or irrigation × rotation × tillage interaction effects on C_{grain} for the 7-yr period.

Irrigation amounts had a significant effect on C_{res} over the seven crop years in this study (Table 4). The fully irrigated plots produced 22.9 Mg ha^{-1} C_{res} when averaged over rotation and tillage system compared with 18.2 Mg ha^{-1} C_{res} for the delayed irrigation system. Rotation had a larger effect on the amount of residue produced. The CC plots, averaged over irrigation and tillage treatments, produced 26.4 Mg ha^{-1} C_{res} during the seven crop years compared with only 20.8 Mg ha^{-1} C_{res} for Rot plots. Rotation had a significant effect on crop residue production every year except 2004 when all plots were in corn. There was a significant interaction between crop rotation and irrigation amounts. The fully irrigated CC plots produced 29.4 Mg ha^{-1} C_{res} while the delayed irrigation CC plots produced 23.3 Mg ha^{-1} of crop residue. The fully irrigated Rot plots produced 16.3 Mg ha^{-1} C_{res} compared with 13.0 Mg ha^{-1} C_{res} for the delayed irrigated plots. Even though the magnitude of differences between irrigation strategies was different, each rotation showed a C_{res} decline of about 20% due to irrigation. There was no significant tillage, rotation × tillage or irrigation × rotation × tillage interaction effects on C_{res} for the 7-yr period.

Because estimated C_{root} (Table 5) and C_{return} (Table 6) are calculated from C_{grain} and C_{res}, the statistical differences exhibited in the measured values are reflected in the calculated values. Irrigation, rotation, and the irrigation × rotation interaction each had a significant main effect on C_{root} and there were no main tillage effect or interactions with tillage.

Bulk density decreased significantly between 2001 and 2008 (Table 7). In 2001 the ρ_b in the 0 to15 cm depth averaged 1.50 Mg m^{-3} and the ρ_b in the 15 to 30 cm depth averaged 1.46 Mg m^{-3}. By 2008 the ρ_b decreased to an average of 1.27 Mg m^{-3} in the 0 to 15 cm depth and 1.26 Mg m^{-3} in the 15 to 30 cm depth. Irrigation treatment had no effect on the change in ρ_b. Crop rotation did not affect the ρ_b in the 0 to 15 cm depth but did affect the amount of change between 2001 and 2008 in the 15 to 30 cm depth. The CC plots decreased an average of 0.16 Mg m^{-3} while the Rot plots decreased an average of 0.24 Mg m^{-3}. Plots with CP decreased ρ_b by an average of 0.28 Mg m^{-3} in the 0 to 15 cm layer compared with a decrease in ρ_b of an average of 0.18 Mg m^{-3} for plots with NT. Tillage had no effect in the magnitude of ρ_b change in the 15 to 30 cm depth. There was no irrigation × rotation, irrigation × tillage or rotation × tillage interactions.

Irrigation did not have a significant effect on the amount of SOC in either 2001 or 2008 at either the 0 to 15 cm or 15 to

Table 4. Carbon content of crop residues (C_{res}) production from spring 2001 to spring 2008.

Irrigation	Tillage†	Rotation‡	2001	2002	2003	2004	2005	2006	2007	Total
			Year							
			Mg ha^{-1}							
Full	NT	CC	3.58	4.91	3.20	4.26	3.45	6.27	4.03	29.70
Full	CP	CC	3.62	5.13	3.48	3.78	2.99	6.26	4.09	29.35
Delayed	NT	CC	2.38	2.92	1.97	3.48	2.84	7.06	3.40	24.05
Delayed	CP	CC	2.44	2.29	2.75	2.30	4.60	4.04	3.30	21.72
Full	NT	Rot	1.81	2.28	1.54	3.83	1.61	2.99	1.66	15.72
Full	CP	Rot	1.78	2.34	1.41	3.27	0.70	2.98	1.52	14.02
Delayed	NT	Rot	1.02	1.85	1.67	2.50	0.88	2.48	1.71	12.10
Delayed	CP	Rot	0.92	1.95	1.46	2.54	0.70	2.57	1.64	11.78
Source§	$P > F$									
Irrigation (I)			0.0054	0.017	0.16	0.13	0.95	0.63	0.13	0.023
Rotation (R)			<0.0001	<0.0001	0.041	0.13	0.0002	0.022	<0.0001	<0.0001
Tillage (T)			0.72	0.55	0.14	0.038	0.91	0.52	0.34	0.38
I × R			0.39	0.0058	0.013	0.84	0.42	0.63	0.12	0.0021
I × T			0.95	0.081	0.21	0.45	0.060	0.36	0.99	0.29
R × T			0.53	0.44	0.0053	0.56	0.25	0.85	0.67	0.95
I × R × T			0.89	0.16	0.46	0.25	0.94	0.91	0.92	0.88

† Tillage systems include no till (NT) and chisel plow (CP).

‡ Rotations include continuous corn (CC) and mixed grass-broadleaf species (Rot).

§ The test for significance of irrigation effects on C_{res} used the irrigation × rep interaction for the error term, crop × irrigation effects were tested using the irrigation × crop × rep interaction for the error term, and tillage × irrigation effects were tested using the irrigation × tillage × rep interaction for the error term.

30 cm depths (Table 8). Both rotations had similar SOC in the 0 to 15 cm and 15 to 30 cm depths in 2001.The CC rotation had greater SOC in the 0 to 15 cm depth in 2008 compared with the Rot treatment. Both rotations had similar SOC at the 15 to 30 cm depth in 2008. Tillage changed the SOC distribution. The NT treatment had greater SOC in the 0 to 15 cm depth in 2008 but both treatments had similar SOC contents in the 15 to 30 cm depth increment.

Irrigation had no effect on ΔSOC over the seven cropping seasons in this study (Table 8). There was a trend toward a greater accumulation of SOC in the delayed irrigation treatment, particularly in the 15 to 30 cm depth. The Rot plots accumulated less SOC than the CC plots between 2001 and 2008. Less SOC was found in the 0 to 15 cm depth of the Rot plots in 2008 than the CC plots but there was a similar amount of SOC at the 15 to 30 cm depth. Overall, the CC plots gained 2.8 Mg ha^{-1} in the 0 to 30 cm soil depth during the seven

Table 5. Estimated carbon provided by root and rhizodeposition (C_{root}) from spring 2001 to spring 2008.

Irrigation	Tillage†	Rotation‡	2001	2002	2003	2004	2005	2006	2007	Total
			Year							
			Mg ha^{-1}							
Full	NT	CC	4.27	3.97	4.41	4.78	3.39	6.87	5.10	32.80
Full	CP	CC	4.43	4.31	4.77	4.50	3.05	6.49	5.01	32.55
Delayed	NT	CC	3.60	2.56	2.56	4.29	3.14	5.63	4.02	25.78
Delayed	CP	CC	3.44	1.95	3.27	2.92	4.64	3.93	3.69	23.84
Full	NT	Rot	1.67	2.70	2.70	4.34	1.92	2.60	1.54	17.48
Full	CP	Rot	1.72	2.67	2.39	3.72	0.70	2.26	1.38	14.84
Delayed	NT	Rot	1.23	2.26	2.80	2.76	0.74	2.12	1.60	13.51
Delayed	CP	Rot	1.14	2.27	2.41	2.53	0.70	1.90	1.41	12.35
Source§	$P > F$									
Irrigation (I)			0.052	0.012	0.087	0.18	0.49	0.068	0.14	0.036
Rotation (R)			<0.0001	0.0014	<0.0001	0.0055	<0.0001	<0.0001	<0.0001	<0.0001
Tillage (T)			0.88	0.56	0.22	0.031	0.80	0.38	0.22	0.19
I × R			0.18	0.014	0.026	0.96	0.39	0.080	0.10	0.052
I × T			0.48	0.074	0.40	0.86	0.097	0.43	0.71	0.73
R × T			0.62	0.69	0.0049	0.69	0.19	0.56	0.47	0.59
I × R × T			0.60	0.11	0.44	0.15	0.92	0.70	0.97	0.47

† Tillage systems include no till (NT) and chisel plow (CP).

‡ Rotations include continuous corn (CC) and mixed grass-broadleaf species (Rot).

§ The test for significance of irrigation effects on C_{root} used the irrigation × rep interaction for the error term, crop × irrigation effects were tested using the irrigation × crop × rep interaction for the error term, and tillage × irrigation effects were tested using the irrigation × tillage × rep interaction for the error term.

Table 6. Estimated carbon returned to soil by crop residues and root and rhizodeposition (C_{return}) from spring 2001 to spring 2008.

Irrigation	Tillage†	Rotation‡	2001	2002	2003	2004	2005	2006	2007	Total
			Year							
			Mg ha^{-1}							
Full	NT	CC	7.85	8.88	7.61	8.94	6.96	13.14	9.24	62.63
Full	CP	CC	8.04	9.44	8.25	8.05	6.04	12.51	9.11	61.43
Delayed	NT	CC	5.97	5.47	4.52	7.77	6.07	12.68	7.51	50.02
Delayed	CP	CC	5.88	4.24	6.02	5.22	9.25	8.04	6.99	45.64
Full	NT	Rot	3.47	4.99	5.48	8.24	3.96	5.64	3.20	34.98
Full	CP	Rot	3.50	5.02	4.78	7.22	1.67	4.91	2.90	30.00
Delayed	NT	Rot	2.24	4.11	5.59	5.26	1.56	4.68	3.31	26.74
Delayed	CP	Rot	2.16	4.22	4.78	5.08	1.54	4.25	2.94	24.97
Source§	$P > f$									
Irrigation (I)			0.019	0.014	0.094	0.19	0.42	0.16	0.14	0.034
Rotation (R)			<0.0001	<0.0001	<0.0001	0.022	<0.0001	0.0001	<0.0001	<0.0001
Tillage (T)			0.78	0.55	0.26	0.021	0.84	0.42	0.21	0.22
I × R			0.30	0.0086	0.028	0.97	0.43	0.38	0.11	0.074
I × T			0.73	0.071	0.30	0.55	0.09	0.37	0.70	0.64
R × T			0.55	0.55	0.0032	0.56	0.21	0.54	0.52	0.75
I × R × T			0.76	0.13	0.38	0.15	0.99	0.65	0.98	0.49

† Tillage systems include no till (NT) and chisel plow (CP).

‡ Rotations include continuous corn (CC) and mixed grass-broadleaf species (Rot)

§ The test for significance of irrigation effects on C_{return} used the irrigation × rep interaction for the error term, crop × irrigation effects were tested using the irrigation × crop × rep interaction for the error term, and tillage × irrigation effects were tested using the irrigation × tillage × rep interaction for the error term.

cropping seasons while the Rot plots lost 0.8 Mg ha^{-1}. Tillage had no significant effect on the total accumulation of SOC but changed the SOC distribution. The NT plots gained 1.7 Mg ha^{-1} in the 0 to 15 cm layer and 0.4 Mg ha^{-1} in the 15 to 30 cm layer for a total increase of 2.1 Mg ha^{-1} for the 0 to 30 cm surface layer of soil. Comparatively, the CP plots lost 2.8 Mg ha^{-1} in the 0 to 15 cm layer of soil but gained 2.7 Mg ha^{-1} in the 15 to 30 cm layer, for a total change of −0.1 Mg ha^{-1} in the surface 0 to 30 cm. There were no treatment interactions on ΔSOC.

There was a significant ($P = 0.008$) positive correlation between C_{return} vs. ΔSOC in the 0 to 30 cm soil layer (Fig. 1). There was not a significant rotation × C_{return} interaction, indicating that the correlation of ΔSOC with C_{return} did not vary by the species producing the crop residue. The regression line of the NT plots crossed the zero change line at 32 Mg ha^{-1} indicating that an average of 4.6 Mg ha^{-1} yr^{-1} C_{return} is needed to maintain SOC levels under the management conditions in this study. The regression line of the CP plots crossed the zero change line at 52 Mg ha^{-1} indicating an average of 7.4 Mg ha^{-1} yr^{-1} C_{return} is needed to maintain SOC levels

DISCUSSION

Maintaining SOC levels should be a primary consideration when designing a cropping system for a specific location and

Table 7. Bulk density (ρ_b) and change in bulk density ($\Delta\rho_b$) between 2001 and 2008 in a Weld loam due to irrigation, crop rotation, and tillage treatments.

Treatment	Variable	ρ_b 0 to 15 cm		ρ_b 15 to 30 cm		$\Delta\rho_b$ 2001 to 2008 0 to 15 cm	$\Delta\rho_b$ 2001 to 2008 15 to 30 cm
		Mg m^{-3}					
Year		2001	2008	2001	2008		
Irrigation (I)	full	1.52	1.29	1.46	1.29	−0.23	−0.17
	delayed	1.49	1.27	1.46	1.23	−0.23	−0.22
Rotation (R) †	CC	1.52	1.30	1.44	1.28	−0.22	−0.16
	Rot	1.50	1.26	1.47	1.23	−0.23	−0.24
Tillage (T)	no till	1.52	1.34	1.46	1.27	−0.18	−0.19
	chisel plow	1.49	1.20	1.46	1.25	−0.28	−0.21
Source‡	$P > f$						
I		0.60	0.52	0.96	0.42	0.85	0.24
R		0.39	0.40	0.14	0.14	0.87	0.028
T		0.28	0.0002	0.52	0.90	0.0091	0.61
I × R		0.17	0.44	0.54	0.38	0.73	0.68
I × T		0.29	0.90	0.95	0.39	0.45	0.65
R × T		0.10	0.42	0.83	0.97	0.75	0.92
I × R × T		0.42	0.92	0.88	0.82	0.58	0.76

† Rotations include continuous corn (CC) and mixed grass and broadleaf crops (Rot).

‡ The test for significance of irrigation effects on ρ_b and $\Delta\rho_b$ used the irrigation × rep interaction for the error term, crop × irrigation effects were tested using the irrigation × crop × rep interaction for the error term, and tillage × irrigation effects were tested using the irrigation × tillage × rep interaction for the error term.

Table 8. Soil organic carbon (SOC) content and change in soil organic C content (ΔSOC) in a Weld loam between 2001 and 2008 due to irrigation, crop rotation, and tillage treatments.

†Irrigation	Tillage†	Rotation‡	SOC 0–15 cm depth 2001	SOC 0–15 cm depth 2008	SOC 15–30 cm depth 2001	SOC 15–30 cm depth 2008	ΔSOC 2001 to 2008 0 to 15 cm depth	ΔSOC 2001 to 2008 15 to 30 cm depth	ΔSOC 2001 to 2008 0 to 30 cm depth
						Mg ha^{-1}			
Full	NT	CC	19.6	24.6	18.7	16.8	5.0	−1.8	3.2
Full	CP	CC	23.7	20.2	13.3	16.3	−3.5	3.0	−0.5
Delayed	NT	CC	18.8	22.1	12.3	15.2	3.3	2.9	6.2
Delayed	CP	CC	18.5	18.1	12.5	14.2	−0.4	1.7	1.3
Full	NT	Rot	21.1	20.5	14.1	14.1	−0.6	0.0	−0.6
Full	CP	Rot	21.0	15.9	13.5	15.6	−5.0	2.1	−2.9
Delayed	NT	Rot	20.0	18.1	13.9	14.0	−1.9	0.1	−1.8
Delayed	CP	Rot	20.1	18.2	12.6	16.4	−1.9	3.8	1.9
Source§	$P > F$								
Irrigation (I)			0.11	0.09	0.40	0.29	0.14	0.76	0.61
Rotation (R)			0.17	0.0087	0.57	0.91	0.033	0.92	0.027
Tillage (T)			0.88	0.0098	0.26	0.41	0.0083	0.10	0.16
I × R			0.41	0.16	0.17	0.12	0.88	0.76	0.87
I × T			0.42	0.41	0.61	0.38	0.20	0.38	0.67
R × T			0.51	0.52	0.64	0.18	0.39	0.49	0.18
I × R × T			0.14	0.20	0.33	0.54	0.73	0.31	0.36

† Tillage systems include no till (NT) and chisel plow (CP).

‡ Rotations include continuous corn (CC) and mixed grass-broadleaf species (Rot).

§ The test for significance of irrigation effects on SOC and ΔSOC used the irrigation × rep interaction for the error term, crop × irrigation effects were tested using the irrigation × crop × rep interaction for the error term, and tillage × irrigation effects were tested using the irrigation × tillage × rep interaction for the error term.

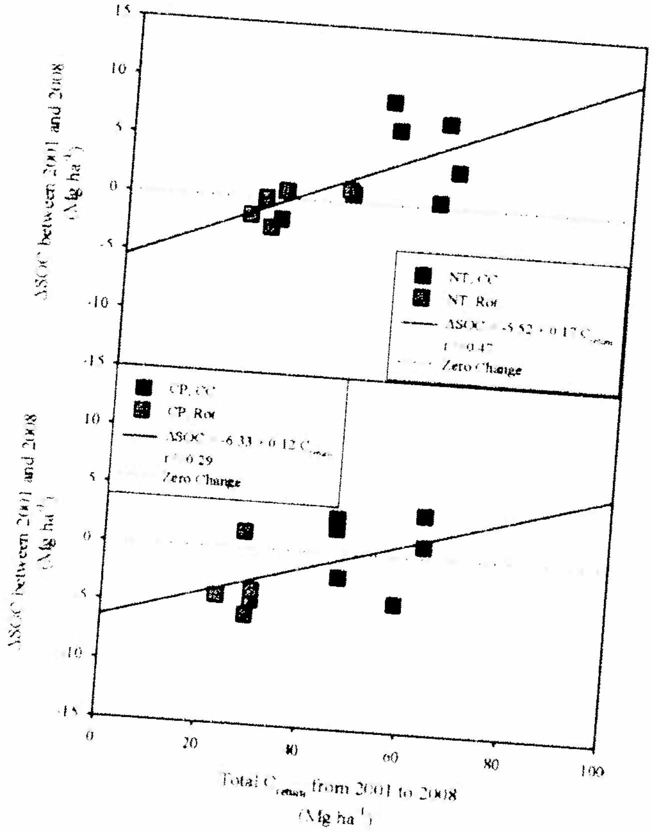

Fig. 1. Relationship of added crop residue C plus estimated added root and rhizodeposition C (C_{return}) on changes in soil organic C (ΔSOC) in the 0 to 30 cm depth increment between 2001 and 2008. NT denotes the no-till cropping system. CP denotes the chisel plow cropping system. CC denotes the continuous corn rotation. Rot denotes the mixed grass and broadleaf crop rotation.

soil type. Obviously, a crop rotation that produces more crop residue will have greater potential for maintaining or increasing SOC than one that produces less residue. However, economic considerations and other goals such as improved pest control or increasing crop diversity can lead the producer to include crops in a rotation that produce a low amount of crop residue.

In this study the soil needed between 4.6 and 7.4 Mg ha^{-1} yr^{-1} C_{return} to maintain SOC for NT and CP management, respectively. These levels are comparable to the 6 Mg ha^{-1} yr^{-1} crop residue addition (3.5 Mg ha^{-1} yr^{-1} C) found by Larson et al. (1972) in southern Iowa and the 7.4 Mg ha^{-1} yr^{-1} crop residue addition (4.3 Mg ha^{-1} yr^{-1} C) found by Pikul et al. (2008) in eastern South Dakota. Larson et al. (1972) and Pikul et al. (2008) did not account for estimates of C_{return} attributed to root and rhizodepostion. There appeared to be no difference in residue source for maintaining SOC in this study.

The broadleaf crops grown in the Rot part of this study did not produce sufficient residue to maintain SOC levels. Red kidney bean produced 2.2 to 3.5 Mg ha^{-1} C_{return}, sunflower produced 2.9 to 5.6 Mg ha^{-1} C_{return}, and spring field pea produced 1.5 to 4.0 Mg ha^{-1} C_{return}. Wheat and barley also failed to provide sufficient C_{return} to maintain SOC. Spring barley produced 4.1 to 5.0 Mg ha^{-1} C_{return} and winter wheat produced 4.2 to 5.6 Mg ha^{-1} C_{return}. Corn was the only crop to provide C_{return} amounts in excess of that required to maintain SOC. These results agree with Wilhelm et al. (2007) who showed a greater need for residue retention in a corn–soybean [*Glycine max* (L.) Merr.] rotation compared with a continuous corn rotation because of low residue production with soybean. Corn C_{return} varied between 4.2 and 13.1 Mg ha^{-1}. Removal of crop residues for off-field use such as for energy production or livestock feed should only come from fields that provide an excess above that which is needed to maintain SOC. Of the crops grown here, only corn consistently provided such levels of residue.

Although the full irrigation treatment produced more crop residue compared with the delayed irrigation treatment, there were no differences in the change of SOC during the time of the study. It is thought that the extra biomass was lost through increased soil microbial activity due to a more favorable water regime in the fully irrigated plots, which is consistent with Denef et al. (2008).

Several studies (Six et al., 1999, 2000; Mikha and Rice, 2004; McVay et al., 2006) have shown that NT systems improve SOC storage greater than tilled systems, particularly in the surface 5 cm of soil. Tillage did not affect the total SOC storage in the surface 30 cm of soil but did change the distribution of SOC. The NT treatment showed an increase in the 0 to 15 cm soil layer while the CP treatment showed a decrease. However, in the 15 to 30 cm layer, the CP treatment showed an increasing trend in SOC, although not significant, while the NT treatment remained unchanged from 2001 to 2008. A possible explanation for the discrepancy in the effectiveness of changing the amount of SOC in the soil is caused by the different depths of sampling among experiments. Christopher et al. (2009), who showed inconclusive results for more SOC sequestered by NT vs. conventional tillage, based their conclusions on a 60 cm soil profile. Bowman et al. (1990), Mikha et al. (2006), and McVay et al. (2006) based their conclusions on a sampling depth of 5 or 7.5 cm.

CONCLUSIONS

Demand for using crop residues for energy production or livestock feed may induce the farmer to remove residues from the field. One must keep in mind that the crop residues are a vital part of maintaining SOC levels in the field and maintaining the beneficial aspects of soil organic matter related to soil chemical and physical properties. We show that, in certain production systems such as continuous corn under irrigation, crop residue is produced in excess of that needed to maintain SOC. These residues could potentially be harvested for off-farm use. These potential harvest levels, however, are much less than the total crop residue production level and any feasibility studies for off-farm use of crop residues should take into account the lower amounts of crop residue that can be harvested without harming the soil resource.

REFERENCES

Allen, R.G. 2000. REF-ET Reference evapotranspiration calculator V 2.01.14. Univ. of Idaho Res. and Ext. Ctr., Kimberly.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration—Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper no. 56. Food and Agric. Organization of the United Nations, Rome.

Allmaras, R.R., D.R. Linden, and C.E. Clapp. 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.

Barber, S.A. 1979. Corn residue management and soil organic matter. Agron. J. 71:625–627.

Benjamin, J.G., M.M. Mikha, and M.F. Vigil. 2008. Organic carbon effects on soil physical and hydraulic properties in a semi-arid climate. Soil Sci. Soc. Am. J. 72:1357–1362.

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

Christopher, S.F., R. Lal, and U. Mishra. 2009. Regional study of no-till effects on carbon sequestration in the Midwest United States. Soil Sci. Soc. Am. J. 73:207–216.

Denef, K., C.E. Stewart, J. Brenner, and K. Paustian. 2008. Does long-term center-pivot irrigation increase soil carbon stocks in semi-arid agro-ecosystems? Geoderma 145:121–129.

Halvorson, A.D., R.F. Follett, C.A. Reule, and S. Del Grosso. 2009. Soil organic carbon and nitrogen sequestration in irrigated cropping systems of the Central Great Plains. p. 141–157. *In* R. Lal and R.F. Follett (ed.) Soil carbon sequestration and the greenhouse effect. 2nd ed. SSSA Spec. Publ. 57. SSSA, Madison, WI.

Halvorson, A.D., and J.M.F. Johnson. 2009. Corn cob characteristics in irrigated Central Great Plains studies. Agron. J. 101:390–399.

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

Jensen, M.E., R.D. Burman, and R.G. Allen. 1990. Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice no. 70. Am. Soc. Civil Eng., New York.

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.

Kim, S., and B.E. Dale. 2004. Global potential bioethanol production from wasted crops and crop residues. Biomass Bioenergy 26:361–375.

Lal, R. 2009. Soil quality impacts of residue removal for bioethanol production. Soil Tillage Res. 102:233–241.

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.

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

Mikha, M.M., and C.W. Rice. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Sci. Soc. Am. J. 68:809–816.

Mikha, M.M., M.F. Vigil, M.A. Liebig, R.A. Bowman, B. McConkey, E.J. Deibert, and J.L. Pikul, Jr. 2006. Cropping system influences on soil chemical properties and soil quality in the Great Plains. Renewable Agric. Food Systems 21:26–35.

Nielsen, D.C., and S.E. Hinkle. 1996. Field evaluation of basal crop coefficients for corn based on growing degree days, growth stage, or time. Trans. ASAE 39:97–103.

Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.G. Lyon, and D.L. Tanaka. 1998. Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil Tillage Res. 47:207–218.

Pikul, J.L., Jr., J.M.F. Johnson, T.E. Schumacher, M. Vigil, and W.E. Riedell. 2008. Change in surface soil carbon under rotated corn in eastern South Dakota. Soil Sci. Soc. Am. J. 72:1738–1744.

Sherrod, L.A., G. Dunn, G.A. Peterson, and R.L. Kolberg. 2002. Inorganic carbon analysis by modified pressure-calcimeter method. Soil Sci. Soc. Am. J. 66:299–305.

Six, J., E.T. Elliott, and K. Paustian. 1999. Aggregate and soil organic matter dynamic under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63:1350–1358.

Six, J., E.T. Elliott, and K. Paustian. 2000. Soil macroaggregates turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32:2099–2103.

Tilman, D., S. Robert, J.A. Foley, J. Hill, E. Larson, L. Lynd, S. Pacala, J. Reilly, T. Searchinger, C. Somerville, and R. Williams. 2009. Beneficial biofuels–The food, energy, and environment trilemma. Science (Washington, DC) 325:270–271.

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.