Irrigated Small-Grain Residue Management Effects on Soil Chemical and Physical Properties and Nutrient Cycling

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Abstract: The effects of straw removal from irrigated fields cropped to wheat and barley on soil properties and nutrient cycling are a concern because of its potential impact on the sustainability of agricultural fields. The increasing demand of straw for animal bedding and the potential development of cellulosic ethanol production will likely increase the demand in the future. Previous reviews addressing changes in soil properties when crop residues are removed focused primarily on rain-fed systems. This article reviews published research assessing the effects of wheat and barley straw removal on soil organic carbon (SOC) and analyzes changes in nutrient cycling within irrigated wheat and barley production systems. The effects of straw removal on bulk density, saturated hydraulic conductivity, and other properties are reported from selected studies. Six studies compared SOC changes with time in irrigated systems in which wheat straw was removed or retained. These studies indicated that SOC either increased with time or remained constant when residues were removed. It is possible that belowground biomass was supplying C to soils at a rate sufficient to maintain or, in some cases, slowly increase SOC with time. A separate research review calculated the minimum aboveground annual carbon inputs needed to maintain SOC levels from nine wheat system studies. Calculations of the minimum aboveground annual C source inputs needed to maintain SOC levels were from rain-fed systems and are some of the best information presently available for use in evaluating residue removal effects in irrigated systems. However, long-term studies are needed to obtain reliable data for diverse irrigated systems. Significant amounts of nutrients are removed from the soil/plant system when straw is removed. Producers will need to determine the cost of the nutrient removal from their systems to determine the value of the straw.

Key words: Straw, residue, wheat, barley, small grain, soil organic carbon, nutrients, fertilizer

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Removal of straw from grain production fields that have historically incorporated the residues with tillage have many interested parties concerned about the effects on soil properties and nutrient cycling. Several changes and potential changes in straw management have led to these concerns, including removal of straw from grain fields for animal bedding and feed, increased costs of fertilizers and fuel, and the potential development of cellulose-based ethanol production.

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Because of potential increases in biofuel demand, the ethanol industry will likely be a major cause of more residue removal from cropland. The immediate and long-term effects of removing aboveground crop residues from fields on crop productivity and sustainability are a concern. A series of policies have pushed for the increased production of biofuels, including the 2000 Biomass Research and Development Act, the 2006 Energy Policy Act, the 2007 Energy Independence and Security Act (mandated a production of 136.2 billion gallons of biofuels by 2022) and the 2002 and 2003 Farm Bill (Biomass Research and Development Initiative, 2008).

Current ethanol production in the United States is primarily from corn grain. However, current research is exploring methods of using cellulose-based products to produce ethanol. Cellulose biomass sources include agricultural crop residues, wood crops, industrial and municipal wastes, lumber wastes, and animal manures (Perlack et al., 2005). Ethanol derived from cellulose is currently the leading candidate of alternative fuel to replace a large portion of the US petroleum-derived fuels (USDOE-NREL, 2006). The US Departments of Energy and Agriculture estimate that 30% of the current US petroleum consumption could be replaced by 1.18 billion Mg of biomass, with modest effects on land-based cropping systems (USDOE-NREL, 2006).

Corn residue has been determined to be the major source of cellulose because of its high stover production per unit of land area (Wilhelm et al., 2004). The large corn production area in the United States, location of these areas, and availability of the corn stover are likely other reasons making corn residue a prime candidate for cellulosic ethanol production. The total stover production in the United States and the top four corn-producing states (Iowa, Illinois, Nebraska, and Minnesota) was estimated at 253.7 and 137 Tg (Tg = 1 billion kilograms) in 2000, respectively (Wilhelm et al., 2004).

Straw produced from small grains such as wheat and barley can also be a source of cellulose for ethanol production (Nelson, 2002; Johnson et al., 2007). Table 1 shows selected statistics (represent means from 2001 to 2006) of wheat and barley production in the United States. The average estimated total annual aboveground biomass from all wheat and barley production from 2001 to 2006 in the United States totals 64.3 Tg (dry weight basis) (USDA-NASS, 2008). Total wheat and barley aboveground biomass represents 25.3% of the stover produced from corn production in the United States in 2000 (253.7 Tg) (Wilhelm et al., 2004). However, under conservation tillage practices, maintaining a base amount of residue will be required to help prevent excessive soil erosion (Nelson, 2002).

The management of crop residues in cropping systems is becoming an important issue in many areas of the United States. Crop residue cycling in soils is important because residues are a major supply of nutrients (N, P, and K) and organic carbon (OC) to soils. A plethora of reported research demonstrates the role of soil OC (SOC) in the plant/soil system. Organic C positively impacts soil fertility, soil structure, water infiltration, water-holding capacity, reduced compaction, and sustains microbial life in soils (Johnson et al., 2006; Tisdale et al., 1993).

TABLE 1. Total Wheat and Barley Grain Production and Estimated Residue Production (dry weight basis) for the Top 10 Producing States in the United States and the Total US Production[†]

State	Grain Yield, Tg[‡]	Residue Yield, Tg[‡§¶]	Percent of US Total
Wheat			
Kansas	8.27	10.11	17.0
North Dakota	6.87	8.40	14.1
Montana	3.44	4.21	7.1
Washington	3.39	4.14	7.0
Oklahoma	3.16	3.86	6.5
South Dakota	2.40	2.93	4.9
Idaho	2.20	2.69	4.5
Texas	2.02	2.46	4.1
Minnesota	2.01	2.45	4.1
Nebraska	1.52	1.86	3.1
U.S. Total	48.69	59.51	100
Barley			
North Dakota	1.51	1.51	31.7
Idaho	0.99	0.99	20.8
Montana	0.71	0.71	14.9
Washington	0.36	0.36	7.5
Minnesota	0.16	0.16	3.4
Colorado	0.16	0.16	3.4
Wyoming	0.12	0.12	2.5
California	0.09	0.09	1.9
Oregon	0.08	0.08	1.7
Arizona	0.07	0.07	1.5
US total	4.78	4.78	100

[†]Values represent averages of USDA-NASS data from 2001 to 2006.
[‡]$Tg = 10^{12}$ g.
[§]Calculated from USDA-NASS wheat bushel (bu) yield data using a test weight of 24 kg (dry weight) bu^{-1} and harvest index of 0.45. Harvest index = grain yield/(grain yield + stover yield).
[¶]Calculated from USDA-NASS barley yield bu data using a test weight of 19.2 kg (dry weight) bu^{-1} and harvest index of 0.5. Harvest index = grain yield/(grain yield + stover yield).

Aboveground crop residues have many benefits in the field. They can act as a physical barrier between the soil and the erosive forces of wind and rain, reduce evaporation, increase water-holding capacity and infiltration, and serve as a nutrient source for future plants.

This article will focus on two issues that tend to be a concern to producers when assessing straw removal from areas that historically have recycled straw in their production systems. These issues include: (i) the effects of straw removal on soil properties and (ii) the effects of straw removal on the economics of nutrient removal. To address these issues, the following objectives will be covered in this article: (i) review published research assessing the effects of wheat and barley residue removal strategies on soil properties in irrigated systems; (ii) evaluate existing literature assessing the minimum C requirements required to maintain SOC levels in rain-fed and irrigated conditions; and (iii) evaluate existing literature on the concentrations of selected nutrients in wheat and barley straw and evaluate the economic considerations when residues are removed.

IRRIGATED GRAIN RESIDUE MANAGEMENT EFFECTS ON SOIL PROPERTIES

Crops supply OC to soils through cycling of aboveground and belowground residues. Molina et al. (2001) estimated that 24% of the net C fixed by corn is deposited in the soil from belowground biomass. Kmoch et al. (1957) reported that the belowground root biomass from plants is similar to the aboveground residue. Gale and Cambardella (2000) found that roots contribute a greater amount of C to the soil C pool than aboveground residues. Amos and Walters (2006) summarized the results from 45 studies assessing the contribution of corn roots to C deposition in soils. They reported that the estimated net belowground C deposition at physiological maturity was 29% ± 13%. The variability associated with total quantities of belowground plant OC production is caused by experimental error associated with sampling and difficulty in quantifying C inputs into the soil from root exudates (Wilhelm et al., 2004). For a more in-depth discussion on belowground inputs of C to soil from plants, refer to earlier reviews (Wilhelm et al., 2004; Johnson et al., 2006, 2007; Amos and Walters, 2006).

Research has been conducted to assess the effects of small-grain residue removal on grain yields, soil physical properties, and soil chemical properties under irrigated conditions (Tables 2 and 3). Bordovsky et al. (1998, 1999) conducted a long-term (11 years) study in the Texas Rolling Plains (North Central Texas), which have soils with poor structure, low organic matter, and low water-holding capacities. The goal of the study was to explore alternate tillage and residue management practices that could improve soil productivity. Undersander and Reiger (1985) conducted a long-term study (14 years) in Etter, TX, to determine if residue burning could be implemented in place of residue incorporation or physical removal of straw to facilitate water movement down furrows. Burning of residue was an attractive option because of the lower fuel costs associated with residue management. Bahrani et al. (2002) conducted a 3-year study in Iran to determine the effects of different residue management options on grain yield and SOC. In the southern provinces of Iran, burning of residues is a common practice (Bahrani et al., 2002). Curtin and Fraser (2003) conducted a 6-year study in New Zealand to determine if cereal straw (wheat, barley, and oat) incorporation in place of burning straw could be implemented to maintain soil organic matter levels. Rates of straw decomposition and selected soil C and N fractions were determined. Follett et al. (2005) conducted a 5-year study in Mexico to determine if conservation tillage could increase SOC under irrigation for wheat and corn rotations.

Grain Yield and Aboveground Biomass

Because of the relationship between grain yield and aboveground biomass (minus grain) and the influence of aboveground residues on SOC, yield data and calculated aboveground biomass from the studies in Table 2 are summarized in this review:

$$AGB = \left(\frac{GW}{HI}\right) - GW \tag{1}$$

where AGB = aboveground biomass (minus grain) (same units as GW), GW = grain weight (same units as AGB), and HI = harvest index.

Bordovsky et al. (1998) measured wheat grain yield in 8 years of their study. The average grain yield and AGB when the residue was removed, during the 8 years under reduced tillage and conventional tillage (3.36 Mg ha^{-1} and 4.11 Mg ha^{-1},

TABLE 2. Research Sources Assessing the Effects of Small-Grain Residue Removal Strategies on Yield, Soil Physical Properties, and Soil Chemical Properties Under Irrigated Conditions

Source	Site	Soil	Duration, Years	Cropping Systems†	Irrigation	Annual Precipitation, mm	Treatment Comparisons‡	Selected Crop and Soil Properties Assessed§
Bordovsky et al. (1999)	Munday, TX	Fine sandy loam	11	Cont. W, S-W double crop (DC)	Furrow	303	1, 2, 3, 4	GY, SY,¶ SOC, BD, K_s, MA
Undersander and Reiger (1985)	Etter, TX	Silty clay loam	14	Cont. W	Furrow	370	1, 2, 5	GY, SY,¶ SOC, IF
Bahrani et al. (2002)	Kushkak, Iran	Clay loam	3	Cont. W	Furrow	400	1, 2, 5	GY, SY,¶ SOC
Curtin and Fraser (2003)	Lincoln, New Zealand	Silt loam	6	W-W-B-B-O-O	Sprinkler	680	1, 2, 5	GY, SY,¶ SOC, BD
Follett et al. (2005)	Mexico	Clay	5	W-C	Boarder	375	2, 5, 6	GY, SY, SOC, BD

†Cont.: continuous; W: wheat; S: sorghum; B: barley; O: oat; C: corn.

‡(1) Residue removed conventional tillage (residue removed after harvest followed by conventional tillage), (2) residue incorporated–conventional tillage (residue incorporated with conventional tillage), (3) residue removed–reduced tillage (residue removed after harvest-reduced tillage), (4) residue surface-reduced tillage (residue left on surface-reduced tillage), (5) residue burned–conventional tillage (residue burned followed by conventional tillage), (6) residue surface–no tillage (residue left on surface–no tillage).

§GY: grain yield; SY: straw yield; IF: irrigation water infiltration; SOC: soil organic carbon; BD: bulk density; K_s: hydraulic conductivity; MA: microaggregation.

¶Calculated using an average harvest index of 0.45 for wheat. Harvest index = grain yield/(grain yield + stover yield).

respectively), were significantly higher than when residue was not removed under both tillage practices (3.16 Mg ha^{-1} and 3.86 Mg ha^{-1}, respectively). Similarly, Bahrani et al. (2002) found that 3-year mean wheat grain yields (6.19 and 6.04 Mg ha^{-1}) and AGB (7.57 and 7.38 Mg ha^{-1}) from burned and residue-removed treatments, respectively, were significantly higher than when residue was incorporated. The difference in yields was likely a result of less weed seed and disease pathogens, and less residue interference during planting (Bordovsky et al., 1998; Bahrani et al., 2002). Follett et al. (2005) also found that average wheat grain yield under the residue burned-convention tillage treatment (Table 2) was significantly higher (6.5 Mg ha^{-1}) compared with the residue incorporated treatment (5.7 Mg ha^{-1}). However, there were no differences in the measured AGB between the residue burned-convention tillage and residue incorporated treatments (11.2 and 10.5 Mg ha^{-1}, respectively). Undersander and Reiger (1985) did not see any long-term differences in wheat grain yields and AGB between residue removed, residue incorporated, or residue burned treatments (average yield and AGB, 3.39 Mg ha^{-1} and 4.14 Mg ha^{-1}, respectively). Curtin and Fraser (2003) measured no effect of

TABLE 3. Tillage Descriptions and Research Site Histories as Reported by Research Sources

Source	Tillage Description	Research Site History
Bordovsky et al. (1999)	Reduced tillage - Chiseled and reshaped beds before planting in Years 5 and 8 of study. No tillage other years Conventional tillage - Disked as needed during summer - Bedded and cultivated before planting	Not Reported
Undersander and Reiger (1985)	Conventional tillage - Broken out and leveled into beds in Year 1 - Disked remaining years	Virgin native short-grass prairie consisting of buffalo grass and blue grama
Bahrani et al. (2002)	Conventional tillage Moldboard plow one time and disked two times	Winter wheat grown previous year
Curtin and Fraser (2003)	Conventional tillage All plots plowed to a depth of 15 cm in fall	- Ryegrass/white clover pasture grown the previous 4 years - Site located in area where 60% of New Zealand's arable crops are grown
Follett et al. (2005)	No tillage - No tillage CT - Moldboard plow one time and disked two times	Conventionally farmed with winter wheat and sorghum grown the previous 2 years

residue management on straw or grain yield during the study except for 1 year when the residue incorporated treatment had a lower grain yield than the residue burned and residue removed treatments.

The time between crops could influence the effect of straw on grain yield because of variations in decomposition times. Three of the reported studies were in a continuous winter wheat system, where wheat was planted in the fall and harvested in the early summer. Therefore, the time between incorporation of residues and planting is 2 to 4 months. Under spring wheat and barley production systems common in many areas of the western United States, the time between harvest and planting is much longer (8–10 months), thus the time for residue breakdown is longer.

Soil Organic Carbon

Bordovsky et al. (1999) reported the SOC concentration in the top 7.5 to 10 cm of soil for a continuous wheat system under both reduced tillage and conventional tillage, and the wheat-sorghum double crop (Table 4). The SOC concentration was determined in 1982, 1985, and 1987. The SOC mass was calculated in 1982 and 1987 from SOC concentration and bulk density (BD) data. Bulk density data were not reported at the start of the study and in 1985. Trends indicate that in 1982, the

TABLE 4. Comparisons of SOC Between Residue Management Practices in Irrigated Wheat-Based Production Systems for Studies Listed in Table 2

Source	Treatment†	Soil Depth, cm	Years After Start of Study				Change‡
Bordovsky et al. (1999)			0	4	7	9	
			SOC g kg^{-1} (Mg ha^{-1})				
	RI-CT (Cont. W)	0–7.5	1.9	3.3 (6.8)	4.6	7.0 (12.8)	5.1 (6.0)
	RR-CT(Cont. W)		1.9	3.3 (6.5)	3.6	4.4 (9.5)	2.5 (3.0)
	RI-RT (Cont. W)		1.9	3.4 (6.6)	6.7	5.9 (11.2)	4 (4.6)
	RR-RT (Cont. W)		1.9	3.4 (6.6)	4.6	4.2 (9.0)	2.3 (2.4)
	RI-RT (S-W DC)		1.9	3.8 (6.9)	8.3	9.7 (15.4)	7.8 (8.5)
	RR-RT (S-W DC)		1.9	4.2 (8.1)	6.5	5.5 (10.0)	3.6 (1.9)
Undersander and Reiger (1985)			0	2	8	14	
			SOC g kg^{-1}				
	RI-CT	0–15	NM§	8.4	12.1	13.5	5.1
	RR-CT		NM	7.2	10.5	12.2	5
	RB-CT		NM	7.3	11.2	11.6	4.3
	RI-CT	15–30	NM	7.1	6.8	7.1	0
	RR-CT		NM	6.9	7.7	6.8	−0.1
	RB-CT		NM	6.2	7.2	6.3	0.1
Bahrani et al. (2002)			0	1	2		
			SOC g kg^{-1}				
	RI-CT	0–30	12.7	13.3	14.4		1.7
	RR-CT		11.9	10.6	12.2		0.3
	RB-CT		12.9	10.8	12.7		−0.2
Curtin and Fraser (2003)			0	6			
			SOC Mg ha^{-1}				
	RI-CT	0–7.5	52.1	54.7			2.6
	RR-CT		52.1	54.4			2.3
	RB-CT		52.2	54.4			2.3
	RI-CT	7.5–15	59.0	58.3			−0.7
	RR-CT		59.0	57.5			−1.5
	RB-CT		59.0	57.0			−2.0
Follett et al. (2005)¶			0	5			
			SOC Mg ha^{-1}				
	RI-CT	0–30	44.3	50.9			6.6
	RS-NT		45.3	62.8			17.5
	RB-CT		45.4	50.3			4.9

†Cont.: continuous; W: wheat; S: sorghum; DC: double crop; RR-CT: residue removed after harvest followed by conventional tillage; RI-CT: residue incorporated with conventional tillage; RR-RT: residue removed after harvest-reduced tillage; RS-RT: residue left on surface-reduced tillage; RB-CT: residue burned followed by conventional tillage; RS-NT: residue left on surface–no tillage.

‡Initial SOC minus SOC at end of study. For Bordovsky et al. (1999), value not in parentheses is SOC concentration (g kg^{-1}) at Year 9 minus Year 0; value in parentheses is difference in SOC mass (Mg ha^{-1}) at Year 9 minus Year 4. Value for Undersander and Reiger (1985) is SOC at Year 2 minus Year 14.

§NM: not measured.

¶Data presented from treatments that received N application rates of 250 kg N ha^{-1} for wheat and 300 kg N ha^{-1} for corn.

SOC concentration (averaged over the three systems) was similar for the residue removed and residue incorporated treatments (3.6 g kg^{-1}), but in 1985 and 1987, the SOC concentration in residue incorporated treatments were 25% and 38% higher than the residue removed treatment, respectively. However, when comparing the SOC over time, SOC concentration and mass in both the residue removed and residue incorporated treatments tended to increase over time (Table 4).

In the study conducted by Bahrani et al. (2002), there was a trend for higher SOC in the 0- to 30-cm soil depth under the residue incorporated treatment 3 years after initiation of the study. The SOC concentration did not significantly decline during this 3-year study, regardless of residue management treatment (Table 4).

Undersander and Reiger (1985) did not show any difference in SOC between residue management treatments (residue burned, residue removed, and residue incorporated) in 1967, 1973, or 1980 (Table 4). The average SOC for all treatments in 1967, 1973, or 1980 was 7.6, 11.3, and 12.4 g kg^{-1} in the 0- to 15-cm depth, and 6.7, 7.2, and 6.7 g kg^{-1} in the 15- to 30-cm soil depth, respectively. In the 0- to 15-cm soil depth, the average SOC over all residue management treatments in 1973 and 1980 (11.3 and 12.4 g kg^{-1}, respectively) was significantly higher than the SOC in 1967 (7.6 g kg^{-1}). However, in the 15- to 30-cm depth, there was no increase in SOC over time.

Curtin and Fraser (2003) showed no difference in total SOC mass between residue management treatments at the end of the 6-year study (Table 4). Follett et al. (2005) found an increase in SOC mass in the 0- to 30-cm depth over 5 years for all treatments receiving N fertilizer (Table 4). The change in SOC for the residue surface–no tillage (residue left on the surface–no tillage) treatment, of a wheat-corn rotation, was higher than the residue incorporated–conventional tillage (residue incorporated with conventional tillage) and residue burned-conventional tillage (residue burned followed by conventional tillage) treatments, which were not different.

The maintenance and increases in SOC over time when residue was removed or burned in these studies are noteworthy and likely result from belowground plant and microbial biomass contributions. These findings are similar to those reported by Campbell et al. (1991), who hypothesized from their results that C from roots contributes more to maintenance of SOC than aboveground wheat residue. The contribution of belowground plant biomass to SOC was not accounted for in these studies. As previously mentioned, understanding the contribution of belowground biomass to SOC is hard to quantify. This can be seen by the variation of values reported in the literature.

Changes in SOC may also be influenced by the fact that when residue is removed from fields, a portion of the aboveground residue remains because of an inability to remove all residues.

The addition of the residues to the soil system did consistently increase the SOC over time at a rate greater than when the residue was removed or burned.

Other Soil Properties

Bordovsky et al. (1999) measured soil BD, saturated hydraulic conductivity (K_s), and microaggregation (MA) in the top 7.5- to 10-cm soil depth in 1982, 1985, and 1987 (Table 5). Data indicate that the incorporation of straw decreased BD and increased K_s and MA. Changes over time for BD and K_s were not apparent from the data presented. Infiltration measurements (24-h measurement period after an April irrigation) taken by Undersander and Reiger (1985) in 1969, 1976, and 1980 did not differ between the residue management treatments. The infiltration measurements averaged for each year over the three residue management treatments were 5.9, 6.6, and 4.3 cm, respectively. The infiltration was lower in 1980 than the previous 2 years because of higher amounts of precipitation during the spring in 1980 compared with 1969 and 1976. The lack of differences between residue management treatments corresponded to the lack of difference with SOC (Undersander and Reiger, 1985). Curtin and Fraser (2003) found no differences in soil BD between residue management treatments (mean BD, 1.14 Mg m^3 at the 0- to 7.5-cm depth and 1.21 Mg m^3 at the 7.5- to 15-cm depth). Follett et al. (2005) found that BD only increased over time in the 0- to 7.5- and 7.5- to 15-cm depths under residue surface–no tillage treatment (increase, 0.16 and 0.11 Mg m^{-3} for the 0- to 7.5- and 7.5- to 15-cm depths, respectively). There were no changes over time in the other two treatments.

Minimum Annual Aboveground Crop Residue Inputs to Maintain SOC

The determined minimum annual aboveground crop residue requirements to maintain SOC levels (MSC) in soils with wheat in cropping systems under irrigated conditions are lacking. However, several studies have determined MCS values under rain-fed conditions. With a lack of data under irrigated conditions, these data under rain-fed conditions can

TABLE 5. Comparisons of Selected Soil Properties (0- to 7.5-cm depth) Between Tillage and Residue Management Practices in Wheat-Based Production Systems (Bordovsky et al., 1999)

Soil Property	Treatment†	Years After Start of Study: 4	9
Bulk density		Mg m^{-3}	
	RI-CT (Cont. W)	1.36	1.20
	RR-CT (Cont. W)	1.30	1.42
	RI-RT (Cont. W)	1.27	1.25
	RR-RT (Cont. W)	1.28	1.40
	RI-RT (S-W DC)	1.19	1.04
	RR-RT (S-W DC)	1.26	1.19
Saturated hydraulic conductivity		$\times 10^{-3}$ cm s^{-1}	
	RI-CT (Cont. W)	0.22	0.46
	RR-CT (Cont. W)	0.21	0.06
	RI-RT (Cont. W)	1.49	2.17
	RR-RT (Cont. W)	1.73	0.99
	RI-RT (S-W DC)	2.14	3.37
	RR-RT (S-W DC)	1.61	2.68
Microaggregation		g kg^{-1}	
	RI-CT (Cont. W)	—	30.7
	RR-CT (Cont. W)	—	27.6
	RI-RT (Cont. W)	—	32.7
	RR-RT (Cont. W)	—	29.1
	RI-RT (S-W DC)	—	36.7
	RR-RT (S-W DC)	—	27.9

†Cont.: continuous; W: wheat; S: sorghum; DC: double crop; RR-CT: residue removed after harvest followed by conventional tillage; RI-CT: residue incorporated with conventional tillage; RR-RT: residue removed after harvest-reduced tillage; RS-RT: residue left on surface-reduced tillage.

TABLE 6. Annual Amount of C and Straw Inputs of Wheat Needed to Maintain Soil Organic C Levels From Reported Research (Information From Johnson et al., 2006)

Citation†	Study Duration, Years	Location	Tillage	Crop	Irrigation‡	MCS,§ Mg ha^{-1} y^{-1}	MSR¶
a	6	Montana	V-blade 9–12 cm	Wheat	NI	0.3	0.75
b	30	Washington	Moldboard plow	Wheat-fallow	NI	4.0	10.0
c	22	Nebraska	Moldboard plow	Wheat-fallow	NI	0.9	2.25
c	84	Colorado	Moldboard plow	Wheat-fallow	NI	1.1	2.75
d	23	Washington	Moldboard plow	Wheat-fallow	NI	1.2	3.0
e	5	Mexico	Moldboard plow	Wheat-corn	I	1.45	3.63
f	31	Sweden	Hand tillage	Wheat-barley	NI	1.5	3.75
g	30	Washington	Moldboard plow	Wheat	NI	2.0	5.0
h	42	Kansas	Moldboard plow	Wheat	NI	2.0	5.0
i	45	Oregon	Moldboard plow	Wheat-fallow	NI	2.1	5.25

†a: Black (1973); b: Horner et al. (1960), Paustian et al. (1997); c: Follett et al. (1997); d: Horner et al. (1960), Rasmussen et al. (1980); e: Follett et al. (2005); f: Paustian et al. (1992); g: Horner et al. (1960), Paustian et al. (1997); h: Hobbs and Brown (1965), Rasmussen et al. (1980); i: Horner et al. (1960), Rasmussen et al. (1980).

‡I: irrigated; NI: not irrigated.

§MCS: minimum aboveground annual C source inputs needed to maintain SOC levels. Values are based on aboveground straw residues and do not include belowground root residues

¶MSR: minimum annual aboveground biomass (AGB) requirement to maintain SOC (Mg ha^{-1} y^{-1}) = C (Mg ha^{-1} y^{-1})/0.4.

serve as a tool for producers making straw-removal decisions. Johnson et al. (2006) determined the MSC values in soils with wheat in cropping systems from several literature reports (Table 6). Most of these studies were conducted under rain-fed systems in environments where water inputs from precipitation are variable. Under irrigation, aboveground and belowground biomass production is stabilized at a high level as long as other management practices (i.e., nutrient and pest management) are adequate. Because of the potential variation in crop biomass production under a rain-fed environment, changes in SOC and other soil properties under rain-fed environments can be different than under irrigation.

TABLE 7. Annual Amount of Wheat Carbon Inputs and Corresponding Grain Yields and Straw Inputs of Wheat Needed to Maintain Soil Organic C Levels From Reported Research (Derived From Johnson et al., 2006)

Citation†	MSC,‡ Mg C ha^{-1} yr^{-1}	Grain Yield,§ Mg ha^{-1}	MSR¶ Mg ha^{-1}
a	0.3	0.61	0.75
b	4.0	8.18	10
c	0.9	1.84	2.25
c	1.1	2.25	2.75
d	1.2	2.45	3.00
e	1.45	2.97	3.63
f	1.5	3.07	3.75
g	2.0	4.09	5.00
h	2.0	4.09	5.00
i	2.1	4.30	5.25
Mean (c-i)	1.5	3.13	3.82

†a: Black (1973); b: Horner et al. (1960), Paustian et al. (1997); c: Follett et al. (1997); d: Horner et al. (1960), Rasmussen et al. (1980); e: Follett et al. (2005); f: Paustian et al. (1992); g: Horner et al. (1960), Paustian et al. (1997); h: Hobbs and Brown (1965), Rasmussen et al. (1980); i: Horner et al. (1960), Rasmussen et al. (1980).

‡MCS: minimum aboveground annual C source inputs needed to maintain SOC levels. Values are based on aboveground straw residues and do not include belowground root residues.

§Grain yield needed to produce sufficient straw to maintain soil organic C levels. Values calculated from linear regression equations (wheat grain yield vs. harvestable biomass).

¶MSR: minimum annual aboveground biomass (AGB) requirement to maintain SOC.

The MSC values from Johnson et al. (2006) for wheat were used to determine the amount of residue that could be harvested at various levels of grain yield (Table 7 and Fig. 1). For example, based on the data collected by Rasmussen et al. (1980), to maintain SOC at levels measured during the study (MCS, 1.2), grain and aboveground biomass (minus grain) yields of 2.5 and 3.0 Mg ha^{-1} would be required. Fig. 1 represents the relationship between grain yield and harvestable aboveground biomass (HAB). Each relationship was derived from the MSC

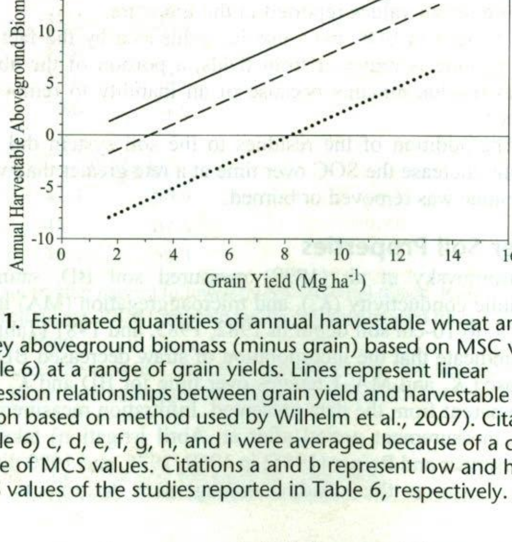

FIG. 1. Estimated quantities of annual harvestable wheat and barley aboveground biomass (minus grain) based on MSC values (Table 6) at a range of grain yields. Lines represent linear regression relationships between grain yield and harvestable straw (graph based on method used by Wilhelm et al., 2007). Citations (Table 6) c, d, e, f, g, h, and i were averaged because of a close range of MCS values. Citations a and b represent low and high MCS values of the studies reported in Table 6, respectively.

values in Table 6. The harvestable straw was calculated as follows:

$$HAB = AGB - MSR \quad (2)$$

where HAB = annual harvestable aboveground biomass (Mg ha^{-1}), AGB = annual aboveground nongrain biomass (Mg ha^{-1}), and MSR = minimum annual AGB requirement to maintain SOC (Mg ha^{-1}). HAB values greater than 0 are the amounts of aboveground residues that can be removed at the corresponding grain yields and still maintain SOC levels.

$$MSR = \frac{MSC}{0.4} \quad (3)$$

Most of the studies did not measure AGB, therefore, they were estimated based on Eq.(1). Harvest Index is the relationship between GW and AGB (Eq.[1]). An average HI value of 0.45 was used for wheat (Johnson et al., 2006). Harvestable aboveground biomass values were calculated at a range of wheat grain yields (1.68, 3.37, 5.05, 6.74, 8.34, 10.1, 11.79, 13.47 Mg ha^{-1}). Linear regression (wheat grain yield versus HAB) was used to calculate grain yields needed to produce MSR values. It is important to note that HI values vary with moisture regimen, N management practices, cultural practices, and year to year. This will change the relationships in Fig. 1.

The variation in MSC values between studies is likely a result of variation in factors such as soil properties, climate, crop sequences, tillage, and experimental error. Based on the reported MSC values from citations c, d, e, f, g, h, and i, the calculated grain yield required to maintain SOC levels is 3.13 Mg ha^{-1} (Table 7). This yield corresponds to an average HAB of 3.82 Mg ha^{-1} (Table 7).

Nutrient Removal

Because wheat and barley straws contain nutrients that are commonly supplemented as fertilizer in many soil systems, understanding the removal rates of these nutrients and the economics of this removal is an important factor for producers to assess. Table 8 summarizes published concentrations of N, P, and K in wheat and barley straw. The N, P, and K concentrations vary by 5.8, 0.87, and 11.02 g kg^{-1} across all citations, respectively. The average N, P, and K masses removed in the straw produced from a wheat yield of 6000 kg ha^{-1} average 52.8, 7.4, and 74.3 kg ha^{-1}, respectively (Table 8). Based on the average high- and low-N, -P, and -K costs from 2000 to 2008 in the United States (USDA-NASS, 2008), the cost of the nutrients per Mg of straw was calculated based on the published concentrations (Table 8). The average low prices for N, P, and K are \$0.48, \$0.24, and \$0.25 kg^{-1}, respectively. The average high prices for N, P, and K are \$1.38, \$0.86, and \$0.86 kg^{-1}, respectively. Averaged across all citations, the total N, P, and K nutrient costs from low to high nutrient costs was \$7.07 to \$21.98 per Mg straw for wheat and \$7.57 to \$24.21 per Mg straw for barley.

Straw removal will change the nutrient cycling dynamics of crop/soil systems compared with systems in which only grain is removed. Compared with grain, straw contains a lower proportion of P and N but a higher proportion of K for both

TABLE 8. Reported Nutrient Concentrations, Masses per Unit Area, and Economics in Wheat and Barley Straw

		Concentration			Mass per Unit Area[†]			Economics[‡]			
Crop Straw	Citation	N	P	K	N	P	K	N	P	K	Total
		-----g kg^{-1}-----			-----kg ha^{-1}------			----------------\$ Mg^{-1}----------------------			
Wheat	Cookson et al. (1998)	5.9	NR[¶]	NR	43.3			2.83–8.14	—	—	—
	Borie et al. (2002)	9.4	1.53	5.88	68.9	11.2	43.1	4.51–12.97	0.37–1.32	1.47–5.06	6.35–19.35
	Jawson and Elliott (1986)	10.6	NR	NR	77.7			5.09–14.63	—	—	—
	Mitchell et al. (2001)	8.2	NR	NR	60.1			3.94–11.32	—	—	—
	Velthof et al. (2002)	6.2	NR	NR	45.5			2.98–8.56	—	—	—
	NRCS Plant Nutrient Content Database (2008)	8.1	0.81	14.8	59.4	5.9	108.5	3.89–11.18	0.19–0.70	3.70–12.73	7.78–24.61
	Mean	8.1	1.2	10.3	59.2	8.6	75.8	3.87–11.13	0.48–1.01	2.59–8.89	7.07–21.98
Barley	Cookson et al. (1998)	6.4	NR	NR	38.4			3.07–8.83	—	—	—
	Andren and Paustian (1987)	6.1	NR	NR	36.6			2.93–8.42	—	—	—
	Christensen (1986)	6	NR	NR	36.0			2.88–8.28	—	—	—
	Mitchell et al. (2001)	7.9	NR	NR	47.4			3.79–10.90	—	—	—
	Velthof et al. (2002)	6.3	NR	NR	37.8			3.02–8.69	—	—	—
	Halvorson and Reule (2007)	4.8	NR	NR	28.8			2.30–6.62	—	—	—
	Arvidsson (1999)	7.1	0.66	16	42.6	4.0	96.0	3.41–9.80	0.16–0.57	4.00–13.76	7.57–24.13
	NRCS Plant Nutrient Content Database (2008)	6.5	0.91	16.9	39.0	5.5	101.4	3.12–8.97	0.22–0.78	4.23–14.53	7.57–24.28
	Mean	6.4	0.8	16.5	38.3	4.7	98.7	3.13–9.00	0.19–0.68	3.29–11.33	7.57–24.21

[†]Wheat and barley straw yields of 7333 and 6000 kg ha^{-1}, respectively, were calculated using harvest indexes of 0.45 for wheat and 0.50 for barley and a grain yield of 6000 kg ha^{-1} for wheat and barley.

[‡]Values are based on average high and low nutrient costs from 2000 to 2008 (USDA-NASS, 2008). Average low prices for N, P, and K are \$0.48, \$0.24, and \$0.25 kg^{-1}, respectively. Average high prices for N, P, and K are \$1.38, \$0.86, and \$0.86 kg^{-1}, respectively. Range is reported as low-high.

[§]Citations only report concentrations.

[¶]NR: not reported.

wheat and barley. The ratios of straw nutrient mass to grain nutrient mass in wheat are 0.47 for N, 0.26 for P, and 4.12 for K. The ratios of straw nutrient mass to grain nutrient mass in barley are 0.49 for N, 0.35 for P, and 5.04 for K. When straw is removed from fields, soil nutrient depletion (especially K) is more rapid compared with harvesting only grain. The overall increased removal of all nutrients will require understanding the changes in the overall nutrient/economic dynamics of the system. Understanding the changes in nutrient cycling with straw removal may also be useful in determining the nutrient balance of individual fields, farms, or even regions. Field-measured nutrient concentrations and straw yields will vary; Table 8 is presented as an example of potential nutrient removal and economic values.

Nutrient removal is a factor that needs to be accounted for when assessing the economics of straw removal. Under scientific-based nutrient management practices, nutrients in soils (obtained from soil sample analysis) are accounted for when determining nutrient recommendations, and increased fertilizer inputs will likely result where residue is removed over the long-term. The true value of the straw to a producer will depend on the need for nutrients in the production system. For example, fields high in soil K may not need fertilizer inputs to replace the nutrients being removed in straw during the short-term. However, during the long-term, nutrient levels in the soil will require inputs. Does the producer place a value over the short-term on the quantity of K removed in the straw? On fields with a history of manure applications, P levels in the soil may be high; therefore straw removal may help lower soil P to more environmentally safe levels over time. Another issue is how to place a value on N. In systems where grain residues remain in the field, most recommendations suggest adding extra N to account for the short-term immobilization of N. Therefore, if straw is removed, theoretically, less N would be recommended for the following crop. However, data show that when straw is removed, N is mined from the soil. How should the long-term removal of N in straw be addressed in the production/economic system? If accounting for the potential long-term impacts, the nutrient value should be included in the market value of the straw. Additional costs will likely need to be added depending on related factors such as residue harvest, transportation, storage, and profit margin.

Many acres of agricultural ground are farmed under rent agreements between tenants and landowners. Producers may be more concerned with short-term economic costs, whereas the landowner may be more concerned with the long-term economic and sustainability impacts. Landowners and producers need to understand the dynamics of nutrient cycling within their systems to make sound production and economic decisions.

DISCUSSION

Rotations including wheat and barley in the irrigated agriculture of the United States can be different compared with those summarized in this article. For example, in the Pacific Northwest, small grain rotations can include alfalfa, corn, potato, and sugar beet. There is very little reported data that can be directly related to these irrigated rotations. To fully understand the impacts of crop residue management on soils, research projects need to be conducted that account for the major crop rotations that include wheat and barley under irrigated conditions. Otherwise, the best data available for dissemination is from research conducted in different environments and systems.

The variation in MSC values found in the literature and the major influence of the residues produced in different crop rotations on SOC point to the importance of rotation-specific and region-specific data acquisition. However, long-term studies are needed to obtain reliable data in this area of research, and the data are not available for many production systems. Long-term research initiated to provide data is costly, and there has to be a significant justification for the future value of the data. At present, best scientific judgments need to be formulated from synthesis of past research data to supply information to the public. Because of the demand for crop residues under current crop/animal systems and the potential demand from cellulose-based biofuel production, the investment in new research projects addressing issues of residue management in irrigated systems under site-specific crop rotations is important in the future of our soil-based agricultural systems.

SUMMARY

Published data assessing the effects of small-grain aboveground residue removal on changes in SOC indicate that irrigated conditions may not be a concern. However, under rainfed conditions, some aboveground residues are needed to maintain SOC levels. Under irrigated conditions, it is possible that belowground biomass is supplying C to soils at a rate to maintain and, in some cases, slowly increase SOC over time.

Significant amounts of nutrients are removed from the soil/plant system when straw is removed. Producers will need to determine the cost of the nutrient removal from their systems to determine the value of the straw.

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