



Small Grain Residue Management Effects on Soil Organic Carbon: A Literature Review

D. D. Tarkalson,* B. Brown, H. Kok, and D. L. Bjorneberg

ABSTRACT

Impact of wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) straw removal from fields on soil organic carbon (SOC) is a concern. Increased animal populations and potential development of cellulosic ethanol production could increase the removal of straw from fields. This paper focuses on the effects of wheat and barley straw removal on SOC in irrigated production systems, and related the results to estimates of the minimum straw carbon inputs required to maintain soil organic carbon (MSC) from rain-fed systems. Six studies compared SOC changes with time in irrigated systems in which wheat straw was removed or retained. These studies indicated that SOC did not decline when residues were removed. Apparently belowground biomass is supplying C to irrigated soils at a rate sufficient to maintain SOC with time. However, under rain-fed systems, returning residue to the soil was required to maintain SOC. Estimates of MSC were obtained from nine rain-fed wheat system studies. Averaged across all rain-fed MSC values, 4.14 Mg more straw ha⁻¹ was required to maintain SOC in rain-fed than in irrigated systems. Presently, the rain-fed based MSC values are the best information available to evaluating residue removal effects but caution should be used in applying these in irrigated systems. The results from this limited number of irrigated studies suggest that rain-fed estimates of MSC will overestimate the MSC in irrigated systems and underestimate the available irrigated straw resources. There is need to evaluate the effect of residue removal on SOC for diverse irrigated systems.

THE IMMEDIATE AND LONG-TERM EFFECTS OF removing aboveground crop residues from fields on soil properties and crop productivity have major implications for the sustainability of agriculture in some regions. Historically much of the crop residue was returned to the soil system in the field. 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, and the potential development of cellulosic-based ethanol production (Johnson et al., 2006; Wilhelm et al., 2007). Increased animal populations in some areas have resulted in more removal of small-grain residues from fields for use as feed and bedding. For example, in an eight-county area of southern Idaho, the dairy population has increased by 258,500 cows from 1990 to 2006.

Use of crop residue as a source for biofuel has received much attention in recent years (USDA-NASS, 2010). A series of policies promoted 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 515.6 billion L of biofuels by 2022) and the 2002 and 2003 Farm Bill (Biomass Research and

Development Initiative, 2008). It is likely that future policies will continue to consider crop residues as sources of energy.

Ethanol derived from cellulose is currently the leading candidate of alternative fuel to replace a large portion of the U.S. petroleum-derived fuels (Perlack et al., 2005). The U.S. Departments of Energy and Agriculture estimate 30% of the current U.S. petroleum consumption could be replaced by 1.18 billion Mg of biomass without large negative effects on land-based cropping systems (Perlack et al., 2005).

Corn (*Zea mays* L.) residue has been determined to be the major source of cellulose (Perlack et al., 2005). 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 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). 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 (Johnson et al., 2006; Nelson, 2002).

The management of crop residues in cropping systems is becoming an important issue in many areas of the United States. Crop residue nutrient cycling in soils is important because residues are a major source of nutrients (N, P, and K) and organic carbon (OC) to soils. A plethora of reported research demonstrates the role of SOC in the plant/soil system. Organic C positively impacts soil

D.D. Tarkalson and D.L. Bjorneberg, USDA-ARS, North West Irrigation and Soils Research Lab., 3793 North 3600 East, Kimberly, ID 83341. B. Brown, Univ. of Idaho Southwest Idaho Research and Extension Center, 29603 U of I Lane, Parma, ID 83660. H. Kok, Coordinator for the Conservation Cropping Systems, Carmel, IN 46032. Received 31 Mar. 2010. *Corresponding author (david.tarkalson@ars.usda.gov).

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Abbreviations: AGB, aboveground biomass (excluding grain); GW, grain weight; HAB, harvestable aboveground nongrain biomass; MSC, minimum straw carbon inputs required to maintain soil organic carbon; MSR, minimum annual aboveground biomass (excluding grain) requirement to maintain soil organic carbon; OC, organic carbon; SOC, soil organic carbon.

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 U.S. production.†

State	Grain yield	Residue yield§¶	Percentage of U.S. 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
U.S. total	4.78	4.78	100

† Values represent averages of USDA-NASS data from 2001 to 2006.

‡ Tg = 10¹² 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 (Johnson et al., 2006). 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 (Johnson et al., 2006). Harvest index = grain yield/(grain yield + stover yield).

fertility, soil structure, water infiltration, water holding capacity, reduced compaction, and sustains microbial life in soils (Johnson et al., 2006; Tisdale et al., 1993). 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 paper will focus on the effects of straw removal on SOC. Many arid areas use irrigation to optimize crop production. Much literature has focused on the effects of residue removal on soil properties under rain-fed conditions but not irrigated conditions. The rain-fed data is the only information used currently to estimate the MSC in irrigated systems. To address this issue the following objectives will be covered in this paper: (i) review published research assessing the effects of wheat and barley residue removal strategies on SOC in irrigated systems and (ii) relate the results to estimates of MSC from rain-fed systems.

IRRIGATED GRAIN RESIDUE MANAGEMENT EFFECTS ON SOIL CARBON

Crops supply OC to soils through cycling of above 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 amount of belowground wheat root biomass from plants was similar to the aboveground residue biomass. 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% of the total C input. The variability associated with total quantities of belowground plant OC production is due to 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 (Table 2 and 3). The research is not extensive but does represent a wide range of irrigated regions. Small grains figure prominently in the irrigated systems studied with small grains grown annually as single or double crops. Therefore, the few studies available may be viewed as worst case scenarios with respect to the amount of small grain residue being removed over time.

Soil Organic Carbon

The quantity of aboveground biomass (minus grain) produced will influence SOC. Grain and aboveground biomass data from studies listed in Table 2 are not presented in this paper but are summarized in Tarkalson et al. (2009).

Bordovsky et al. (1998, 1999) conducted a long-term (11 yr) study in the Texas Rolling Plains (North Central Texas) which have soils with poor structure, low organic matter, and low water holding capacity. The goal of the study was to explore alternate tillage and residue management practices that could improve soil productivity. They reported the SOC concentration in the 7.5 to 10 cm of soil for a continuous wheat system under both reduced tillage and conventional tillage, and the wheat–sorghum (*Sorghum bicolor* L.) double crop (Table 4). The SOC concentration was determined for the entire study site in 1978 and for each treatment in 1982, 1985, and 1987. Soil organic C mass was calculated in 1982 and 1987 from SOC concentration and bulk density data. Bulk density data were not reported in 1978 or 1985. Residue-incorporated treatments had a 2.5 times greater rate of SOC change than the residue-removed treatments. 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).

Bahrani et al. (2002) conducted a 3-yr study in Iran to determine the effects of different wheat residue-management options on wheat grain yield and SOC. In the southern provinces of Iran, burning of residues is a common practice (Bahrani et al., 2002). They found a trend for higher SOC in the 0- to 30-cm soil depth under the residue-incorporated treatment 3 yr after initiation of the study. The SOC concentration did not decline significantly during this 3-yr study, regardless of residue-management treatment (Table 4).

Undersander and Reiger (1985) conducted a long-term study (14 yr) in Etter, TX to determine if wheat residue burning could

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	Cropping systems†	Irrigation	Annual precipitation	Treatments comparisons‡
Bordovsky et al. (1999)	Munday, TX	fine sandy loam	11 yr	Cont. W, S-W double crop (DC)	furrow	303 mm	1, 2, 3, 4
Undersander and Reiger (1985)	Etter, TX	silty clay loam	14	Cont. W	furrow	370	1, 2, 5
Bahrani et al. (2002)	Kushkak, Iran	clay loam	3	Cont. W	furrow	400	1, 2, 5
Curtin and Fraser (2003)	Lincoln, New Zealand	silt loam	6	W-W-B-B-O-O	sprinkler	680	1, 2, 5
Follett et al. (2005)	Mexico	clay	5	W-C	boarder	375	2, 5, 6

† 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).

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. Results from their study did not show any difference in SOC among residue-management treatments in 1967, 1973, or 1980 (Tarkalson et al., 2009). The rate of SOC change in the 0- to 15-cm soil depth was positive and similar for all residue management treatments (average = 0.40 g kg⁻¹ yr⁻¹) (Table 4). In the 15- to 30-cm depth there was no change in SOC over time.

Curtin and Fraser (2003) conducted a 6-yr study in New Zealand to determine if cereal straw (wheat, barley, and oat [*Avena sativa* L.]) 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. They found no difference in total SOC mass with residue-management treatments at the end of the 6-yr study. Trends indicate an increase in SOC over time in the 0- to 7.5-cm soil depth and a decline in the 7.5- to 15-cm depth (Table 4). The average net difference in rate of SOC change between the depths is 0.16 Mg kg⁻¹ yr⁻¹.

Follett et al. (2005) conducted a 5-yr study in Mexico to determine if conservation tillage could increase SOC under irrigation for wheat and corn rotations. They found an increase in SOC mass in the 0- to 30-cm depth over 5 yr 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 in irrigated systems over time in these studies when residue was removed or burned is likely a result of belowground plant root and microbial biomass C contributions. These findings are similar to those Campbell et al. (1991) reported, who hypothesized from their results that C from roots contribute more to maintenance of SOC than aboveground wheat residue. The contribution of belowground plant biomass to SOC was not accounted for in the reported studies (Table 2). As previously mentioned, the contribution of belowground biomass to SOC is hard to quantify. This can be seen by the variation of values reported in the literature.

The addition of the residues to the soil system consistently increased SOC over time at a rate greater than when the residue was removed or burned. Changes in SOC may also be influenced by the fact that when residue is removed from fields, a portion of the aboveground residue remains due to an inability to remove all residues.

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 year 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 buffalograss 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 15cm in fall.	-Ryegrass/white clover pasture grown the previous 4 yr. -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 yr.

Table 4. Changes in soil organic carbon (SOC) for residue management practices in irrigated wheat-based production systems for studies listed in Table 2. Actual soil organic C values from reported years are presented in Tarkalson et al. (2009).

Source	Treatment†	Soil depth cm	Rate of SOC change‡	
			g kg ⁻¹ yr ⁻¹	Mg ha ⁻¹ yr ⁻¹
Bordovsky et al. (1999)	RI-CT (Cont.W)	0–7.5	1.02	1.20
	RR-CT (Cont.W)		0.28	0.60
	RI-RT (Cont.W)		0.44	0.92
	RR-RT (Cont.W)		0.26	0.48
	RI-RT (SW DC)		0.87	1.70
	RR-RT (SW DC)		0.40	0.38
Undersander and Reiger (1985)	RI-CT	0–15	0.43	—§
	RR-CT		0.42	–
	RB-CT		0.36	–
	RI-CT	15–30	0	–
	RR-CT		–0.0083	–
	RB-CT		0.0083	–
Bahrani et al. (2002)	RI-CT	0–30	0.85	–
	RR-CT		0.15	–
	RB-CT		–0.10	–
Curtin and Fraser (2003)	RI-CT	0–7.5	–	0.43
	RR-CT		–	0.38
	RB-CT		–	0.38
	RI-CT	7.5–15	–	–0.12
	RR-CT		–	–0.25
	RB-CT		–	–0.33
Follett et al. (2005)¶	RI-CT	0–30	–	1.32
	RS-NT		–	3.50
	RB-CT		–	0.98

† Cont. W = continuous wheat, SW DC = sorghum-wheat 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.

‡ (SOC end–SOC initial)/total years of study. For Bordovsky et al. (1999), g kg⁻¹ yr⁻¹ value represents change from study start to year 9. Mg kg⁻¹ yr⁻¹ value represents change from year 4 to 9. Value for Undersander and Reiger (1985) is change in SOC from year 2 to 14.

§ Not reported or unable to calculate.

¶ 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.

MINIMUM STRAW CARBON INPUTS TO MAINTAIN SOIL ORGANIC CARBON

The MSC in soils with wheat in cropping systems under irrigated conditions is lacking. However, several studies have determined MSC values under rain-fed conditions. Johnson et al. (2006) determined the MSC values in soils with wheat in cropping systems from several literature reports (Table 5). Most of these studies were conducted under rain-fed systems in environments where water from precipitation is variable. Under irrigation, above 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.

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 5 and Fig. 1). For example, based on the data that Rasmussen et al. (1980) collected, to maintain SOC at levels measured during the study (MSC = 1.2 Mg C ha⁻¹ yr⁻¹) grain and aboveground biomass (minus grain) yields of 4.3 and 3.0 Mg ha⁻¹ would be required,

respectively. Figure 1 represents the relationship between grain yield and harvestable aboveground biomass. Each relationship was derived from the MSC values in Table 5. The harvestable straw was calculated as follows:

$$HAB = AGB - MSR \quad [1]$$

where HAB = annual harvestable aboveground biomass (Mg ha⁻¹) AGB = annual aboveground nongrain biomass (Mg ha⁻¹) and MSR is the minimum annual aboveground biomass (excluding grain) requirement to maintain SOC (Mg ha⁻¹).

$$AGB = \left(\frac{GW}{HI} \right) - GW \quad [2]$$

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

$$MSR = \frac{MSC}{0.4} \quad [3]$$

Most of the studies did not measure AGB, therefore they were estimated based on Eq. [1]. Harvest index is the relationship between

Table 5. Annual amount of wheat C and straw inputs and corresponding grain needed to maintain soil organic C levels from reported research (minimum straw carbon inputs required to maintain soil organic carbon [MSC] information for studies obtained from Johnson et al., 2006).

Citation†	Study duration yr	Location	Tillage	Crop	Irrigation‡	MSC§	Mg ha ⁻¹ yr ⁻¹	
							MSR¶	Grain yield#
a	6	Montana	V-blade 9–12 cm	wheat	NI	0.3	0.75	0.61
b	30	Washington	moldboard plow	wheat–fallow	NI	4.0	10.0	8.18
c	22	Nebraska	moldboard plow	wheat–fallow	NI	0.9	2.25	1.84
c	84	Colorado	moldboard plow	wheat–fallow	NI	1.1	2.75	2.25
d	23	Washington	moldboard plow	wheat–fallow	NI	1.2	3.0	4.30
e	5	Mexico	moldboard plow	wheat–corn	I	1.45	3.63	2.45
f	31	Sweden	hand tillage	wheat–barley	NI	1.5	3.75	2.97
g	30	Washington	moldboard plow	wheat	NI	2.0	5.0	3.07
h	42	Kansas	moldboard plow	wheat	NI	2.0	5.0	4.09
i	45	Oregon	moldboard plow	wheat–fallow	NI	2.1	5.25	4.09
					Mean	1.66	4.14	3.39

† 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.

§ Values are based on aboveground straw residues and do not include belowground root residues. Assuming 0.4 kg C kg residue⁻¹.

¶ MSR = minimum annual aboveground biomass (excluding grain) requirement to maintain SOC. MSC/0.4.

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).

GW and AGB (Eq. [2]). Average HI value for wheat was 0.45 (Johnson et al., 2006). Harvestable aboveground biomass values were calculated for 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 vs. HAB) was used to calculate grain yields needed to produce MSR values. It is important to note the HI values may vary with changing cultural and environmental conditions.

The variation in MSC values between studies was likely a result of variation in factors such as soil properties, climate, crop sequences, tillage, and experimental error. Based on the average MSC value (1.66 Mg C ha⁻¹) from all citations, the

average calculated grain yield and minimum annual aboveground biomass (excluding grain) requirement to maintain SOC levels were 3.34 and 4.14 Mg ha⁻¹, respectively (Table 5).

DISCUSSION

This review points out contradictory conclusions regarding effects of residue removal on SOC under irrigated and rain-fed conditions. Published data assessing the effects of small grain residue removal on changes in SOC indicate with irrigated conditions that it may not be a concern. Under irrigated conditions it is possible that belowground biomass is supplying C to soils at

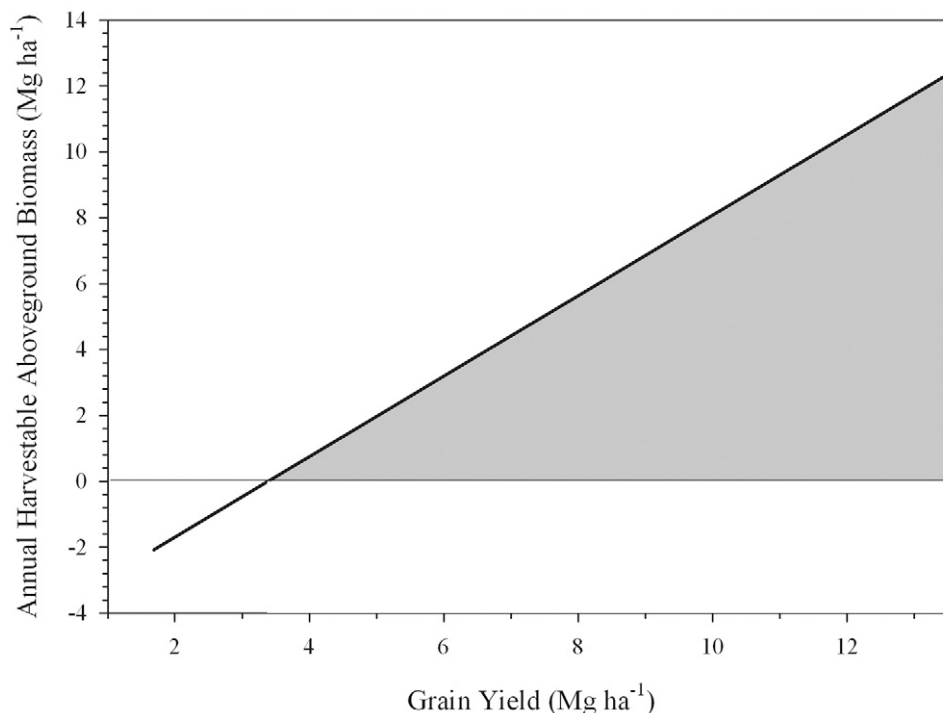


Fig. 1. Estimated quantities of annual harvestable wheat and barley aboveground biomass (minus grain) based on minimum straw carbon inputs required to maintain soil organic carbon (MSC) values (Table 5), at a range of grain yields. For example, wheat straw in the shaded area would be sustainably harvestable. Line represents average linear regression relationships between grain yield and harvestable straw for references a-i in Table 5 (Graph based on method used by Wilhelm et al., 2007).

a rate to maintain and in some cases slowly increase SOC over time. However, under rain-fed conditions some aboveground residue is needed to maintain SOC levels. It is possible that the levels of initial SOC may be much lower in relation to the equilibrium SOC levels in irrigated systems compared to rain-fed systems. This theory will need additional exploration.

The implications for estimated HAB from irrigated systems are significant. Estimates of HAB from rain-fed systems should not be used for irrigated systems. To do so would possibly underestimate HAB resources available in irrigated systems where small grains figure as prominently as they do in the reported studies.

Rotations including wheat and barley in the irrigated agriculture of the United States can differ from those summarized in this paper. For example, in the Pacific Northwest, small grain rotations can include alfalfa (*Medicago sativa* L.), corn, potato (*Solanum tuberosum* L.), and sugarbeet (*Beta vulgaris* L.). Also, there is very little of the reported data that can be directly related to these irrigated rotations in part because small grains are seldom grown continuously. The limited data from irrigated systems provide little indication of the relative importance of small grain residues for SOC maintenance when irrigated small grains are grown only once in a 3 to 5 yr annual crop rotation. To fully understand the impacts of crop residue management on soils, research studies need to be conducted that account for the major irrigated crop rotations that include wheat and barley. Otherwise the data available for dissemination is from research conducted in different environments and systems that may not be appropriate.

The variation in MSC values found in the literature and the major influence of the residues produced in different crop rotations on SOC, points to the importance of rotation-specific and region-specific data acquisition. However, long-term studies are needed to obtain reliable data in this area, and the data are not available for many production systems. Long-term research initiated to provide data is costly and there needs to be a significant justification for the future value of the data. In the 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 with current crop/animal systems and the potential demand from cellulose based biofuels, the investment in new research projects addressing issues of residue management in irrigated systems under site-specific crop rotations are important investments in the future of our soil-based agricultural systems.

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