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Soil and crop response to stover removal from rainfed and irrigated corn

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Abstract

Excessive corn (*Zea mays* L.) stover removal for biofuel and other uses may adversely impact soil and crop production. We assessed the effects of stover removal at 0, 25, 50, 75, and 100% from continuous corn on water erosion, corn yield, and related soil properties during a 3-year study under irrigated and no-tillage management practice on a Ulysses silt loam at Colby, irrigated and strip till management practice on a Hugoton loam at Hugoton, and rainfed and no-tillage management practice on a Woodson silt loam at Ottawa in Kansas, USA. The slope of each soil was <1%. One year after removal, complete (100%) stover removal resulted in increased losses of sediment by 0.36–0.47 Mg ha^{-1} at the irrigated sites, but, at the rainfed site, removal at rates as low as 50% resulted in increased sediment loss by 0.30 Mg ha^{-1} and sediment-associated carbon (C) by 0.29 kg ha^{-1}. Complete stover removal reduced wet aggregate stability of the soil at the irrigated sites in the first year after removal, but, at the rainfed site, wet aggregate stability was reduced in all years. Stover removal at rates ≥ 50% resulted in reduced soil water content, increased soil temperature in summer by 3.5–6.8 °C, and reduced temperature in winter by about 0.5 °C. Soil C pool tended to decrease and crop yields tended to increase with an increase in stover removal, but 3 years after removal, differences were not significant. Overall, stover removal at rates ≥50% may enhance grain yield but may increase risks of water erosion and negatively affect soil water and temperature regimes in this region.

Keywords: stover removal, water erosion, soil aggregation, soil carbon, irrigation

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Introduction

The demand for corn stover feedstock for bioenergy production and other competing uses is expected to increase in the near future. Corn stover has been identified as a prime feedstock for bioenergy production in the United States because of its perceived abundance and availability (Wilhelm *et al.*, 2004; United States Department of Agriculture, 2010). Although the use of corn stover for bioenergy production and other expanded uses appears to be feasible, the magnitude at which different levels of stover removal affect soil erosion, soil properties, crop production, and other ecosystem services is not well understood in the western Corn Belt in general and Kansas in particular. This information is needed for determining the amount of stover that can be harvested for biofuel from rainfed and irrigated conditions.

Removal of stover for bioenergy may negatively affect ecosystem services provided by crop residues such as erosion control (Cruse & Herndl, 2009). Even soils under no-till management may be affected if residues are removed at high rates. On silt loam and sandy loam no-till soils in Iowa, Laflen & Colvin (1981) found that a decrease in stover cover resulted in an exponential increase in sediment loss. On a silt loam in Illinois, 100% stover removal resulted in increased sediment loss from 0.1 to 1.3 Mg ha^{-1} (Bradford & Huang, 1994). Differences in soil slope, amount of stover removal, and cropping systems may affect the extent at which stover removal increases erosion (Gilley *et al.*, 1986; Unger, 1992).

Although the importance of crop residues for protecting soil from erosion is well recognized (Meyer *et al.*, 1970; Gilley *et al.*, 1986; Lindstrom, 1986; Adekalu *et al.*, 2007), information on how different levels of stover

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removal affect soil erosion is limited. In regions with limited precipitation but intense and localized rainstorm events such as the central Great Plains, high rates of stover removal may increase risks of water erosion. This can be particularly a concern under increasing climatic fluctuations.

Stover removal may also degrade soil physical properties and reduce soil C pool. In South Dakota, Hammerbeck *et al.* (2012) reported that stover removal reduced mean weight diameter of both 0.84–2.0 mm water-stable aggregates and >19.2 mm dry aggregates from no-till corn-soybean rotation after 8 years of management. The same study reported that stover removal reduced concentration of soil organic matter and particulate organic matter in all aggregate size fractions. In Ohio, stover removal reduced aggregate stability and total soil C near the soil surface in the short term (<3 year; Blanco-Canqui *et al.*, 2006; Blanco-Canqui & Lal, 2007). An increase in stover removal rate may also increase soil temperature fluctuations (Sharratt, 2002), increase evaporation (Flerchinger *et al.*, 2003), and decrease plant available water (Blanco-Canqui & Lal, 2007; Moebius-Clune *et al.*, 2008).

Stover removal impacts on crop yields can be inconsistent. Stover removal may (Wilhelm *et al.*, 1986; Blanco-Canqui & Lal, 2007; Varvel *et al.*, 2008) or may not (Karlen *et al.*, 1994) reduce crop yields, depending on the management and site-specific conditions. Excessively wet and cold soils during the germination period under stover mulch may delay emergence and reduce crop yields in some soils (Swan *et al.*, 1994). Furthermore, stover removal may not affect corn yield in fertile soils (Karlen *et al.*, 1994), particularly in the short term, but it may rapidly reduce corn yield in erosion-prone soils. In Ohio, grain yield decreased by 1.95 Mg ha^{-1} under 50 and 75% removal rates and by 3.32 Mg ha^{-1} under 100% removal on a water erosion-prone soil, but differences in grain yield due to stover removal were not significant in soils where water erosion was not a major constraint (Blanco-Canqui & Lal, 2007). In eastern Nebraska, averaged across 4 years, each Mg ha^{-1} of stover removed reduced grain yield by 0.1 Mg ha^{-1} and stover yield by 0.30 Mg ha^{-1} (Wilhelm *et al.*, 1986). Another study in eastern Nebraska found that, averaged across 5 years, 51% stover removal consistently reduced grain and stover yield under rainfed conditions (Varvel *et al.*, 2008).

Experimental data on the effects of different levels of stover removal on water erosion, soil properties, and crop production are sparse. This is particularly true for irrigated conditions. Data from both rainfed and irrigated corn production systems are needed for a better understanding of stover removal impacts on soil and crop production. Thus, the objectives of this study were to determine the effects of different levels of stover removal on water erosion, corn yield, and related soil properties under rainfed and irrigated conditions during 3 years following stover removal from no-till and reduced till systems in three soils in Kansas.

Materials and methods

Description of study sites

We conducted this study for 3 years on three corn stover removal experiments in Kansas established in spring 2009. The three sites were at the (i) Kansas State University (KSU)-Northwest Research Extension Center in Colby (39°23′N, 101°03′W, 969 m above sea level); (ii) a private producer's field near Hugoton (37°21′N, 101°20′W, 940 m above sea level); and (iii) KSU-East Central Experiment Field in Ottawa (38°32′N, 95°15′W, 294 m above sea level) (Fig. 1). These sites differ in soil texture, climate, and management practices (Table 1). The soil texture is silt loam at Ottawa and Colby, and loam at Hugoton (Table 1). The soil slope was <1% at all sites. Precipitation data for the study period (2009, 2010, and 2011) and 10- and 30-year averages are reported in Table 2.

The sites at Ottawa and Colby were managed under no-till, while the site at Hugoton was strip tilled (Table 1). The site at Ottawa is rainfed, while the sites at Colby and Hugoton are sprinkler irrigated. Management practices prior to the experiment onset varied among sites. At Colby, conventionally tilled, irrigated sunflower (*Helianthus annuus*, L.), corn, and soybean (*Glycine max* L.) were grown in 2006, 2007, and 2008, respectively. The Hugoton site had been in strip tilled, irrigated, continuous corn for 3 years prior to this study. The Ottawa site had been in rainfed, no-till, continuous corn for 5 years prior to this study.

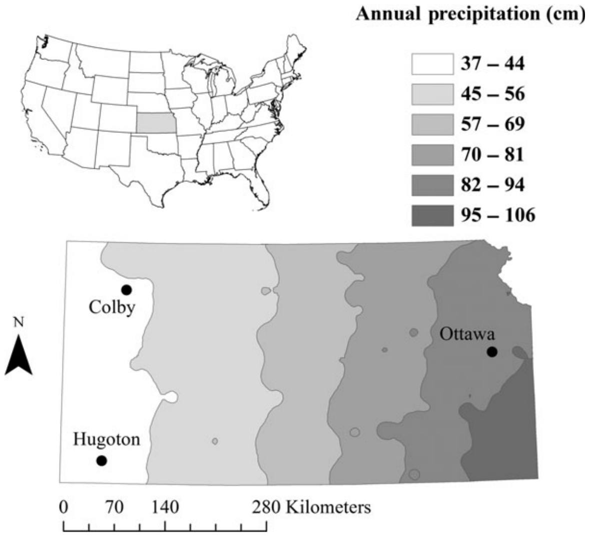

Fig. 1 Location of the study sites in Kansas. The site at Ottawa is rainfed, while the sites at Colby and Hugoton are sprinkler irrigated.

Table 1 Soil characteristics, climate, and management of the three study sites. Soil slope is ≤1% at all sites

Site	Soil series	Taxonomic classification	Mean minimum temperature (°C)	Mean maximum temperature (°C)	Mean annual precipitation (mm)	Management	Tillage system
Colby	Ulysses silt loam	Fine-silty, mixed, superactive, mesic Aridic Haplustolls	3.0	17.7	470	Irrigated continuous corn	No-till
Hugoton	Hugoton loam	Fine-silty, mixed, superactive, mesic Aridic Argiustolls	5.9	19.8	457	Irrigated continuous corn	Reduced till
Ottawa	Woodson silt loam	Fine, smectitic, thermic Abruptic Argiaquolls	6.3	18.4	953	Rainfed continuous corn	No-till

A randomized complete block design with five treatments in triplicate was laid out in 6 by 6 m plots at each site in spring 2009. The five treatments consisted of removing 0, 25, 50, 75, and 100% of stover after corn harvest each year. At project initiation in spring 2009, corn stover remaining from the previous year harvest (2008) was redistributed in the treatment plots at each site. Subsequently, in fall 2009, 2010, and 2011, corn stover after harvest was redistributed in each treatment plot for each site.

At harvest, plants were cut with shears leaving 15 cm of stalk above the soil surface to simulate common combine stalk cutting heights. Percent stover removal was estimated by dividing each plot into four quadrants, removing stover from the appropriate number of quadrants in each plot, and thoroughly redistributing the remaining stover across the whole plot to obtain a uniform surface cover. It is important to reiterate that about 15 cm of stalk was left in the field on all plots. The dry mass of stover removed for each site is presented in Table 3.

Corn was planted with 76 cm row spacing at all sites in May 2009, 2010, and 2011. It was planted at 76 601 seeds ha^{-1} at Colby, 85 250 seeds ha^{-1} at Hugoton, and 63 258 seeds ha^{-1} at Ottawa. Plots were fertilized with 202 kg N ha^{-1}, 8 kg Zn ha^{-1}, and 26 kg S ha^{-1} at Colby, 134 kg N ha^{-1}, 15 kg P ha^{-1}, and 9 kg K ha^{-1} at Ottawa, and 11.8 l N ha^{-1}, 18 l N ha^{-1}, and 22.4 kg N ha^{-1} at Hugoton. At each site, weeds were controlled with atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine), S-metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide), and glyphosate (*N*-(phosphonomethyl) glycine).

Rainfall simulation

Rainfall was simulated in the spring of 2010 (1 year after stover removal) to determine runoff, sediment, and sediment-associated C losses from each study site. A rainfall simulator with a single nozzle (Miller, 1987) rained on 2.5 m^2 runoff subplots established inside the 36 m^2 main plots. A V-shaped runoff collector was installed at the down slope end of each runoff plot to funnel runoff into plastic 4 l graduated buckets. Rainfall simulation was conducted on one runoff plot in each treatment plot.

Simulated rainfall was applied for 30 min with an intensity of 91 mm h^{-1} at Ottawa, and 76 mm h^{-1} at Colby and Hugoton, representing rainstorms with a 5-year return interval for each site (Hershfield, 1961). Average wind speed during rainfall simulations was about 3.1 m s^{-1} at Hugoton and 4.9 m s^{-1} at Colby and Ottawa. The relatively strong winds during simulations were a major constraint for this study and reflected the typical weather conditions in Kansas. Dry and wet runs were performed in each plot. Dry runs were done 24 h before wet runs to ensure that antecedent soil water content was similar in all treatment plots. For each simulation, one-liter runoff subsample was taken from the collection buckets for the determination of sediment concentration, which was done by oven drying subsamples at 60 °C. The sediment was analyzed for total C concentration by dry combustion (Nelson & Sommers, 1996) to determine sediment-associated C concentration.

Determination of soil properties and corn yields

Changes in wet aggregate stability, soil C pool, soil water content, soil temperature, and grain and stover yields as affected by stover removal were monitored for each site for 3 years. One soil sample from each plot was collected for the determination of bulk density, wet aggregate stability, and soil total C and total N concentration. Soil was sampled for aggregate stability from the 0–5 cm soil depth in spring 2010, 2011, and 2012. Samples were air-dried and sieved to collect aggregates 4.75–8 mm in size for determination of water-stable aggregates

Table 2 Precipitation data for the three study sites from 2009 to 2011

		Precipitation data (mm)				
Site	Month	2009	2010	2011	10-year Average	30-year Average
Colby	January	4	4	6	6	8
	February	12	10	5	9	9
	March	3	44	14	23	30
	April	87	67	48	55	40
	May	140	68	59	62	93
	June	94	75	50	68	81
	July	97	101	146	76	80
	August	85	65	80	74	52
	September	39	17	11	35	43
	October	79	6	74	50	27
	November	10	5	6	12	15
	December	18	4	17	19	9
	Annual	668	465	516	488	486
Hugoton	January	51	10	2	23	12
	February	8	13	3	7	10
	March	23	56	1	26	30
	April	65	24	21	30	37
	May	8	130	7	50	65
	June	121	125	81	103	91
	July	60	111	34	45	65
	August	22	70	66	84	67
	September	11	0	36	54	45
	October	78	9	17	41	34
	November	10	5	51	17	14
	December	1	5	61	29	17
	Annual	458	558	378	507	486
Ottawa	January	4	14	23	34	31
	February	10	50	92	43	37
	March	57	45	62	62	68
	April	188	119	66	99	98
	May	70	135	152	130	137
	June	182	146	88	163	143
	July	112	190	45	113	104
	August	151	35	69	107	103
	September	153	166	45	104	105
	October	117	42	9	79	84
	November	65	40	119	50	69
	December	69	7	75	45	45
	Annual	1179	989	845	1027	1024

by the wet-sieving method (Kemper & Rosenau, 1986). A quantity of 50 g of air-dry aggregates was placed on the top sieve of a column of nested sieves with mesh openings of 4.75, 2.00, 1.00, 0.50, and 0.25 mm, saturated by capillarity with water for 10 min, and then mechanically sieved in water for 10 min sieved in water through a vertical displacement of 35 mm at 30 oscillations min^{-1}. The soil remaining on each sieve was washed into pre-weighed beakers and oven dried at 105 °C for 48 h to obtain soil mass. The oven-dry soil was soaked in a 13.9 g l^{-1} sodium hexametaphosphate solution for 24 h to disperse soil aggregates and then washed for sand correction (Nimmo & Perkins, 2002).

For the determination of total C and N, soil was sampled in spring 2010, 2011, and 2012 from 0 to 5 cm depth, air-dried, ground with mortar and pestle, and sieved to 0.25 mm for measurement of total C and N concentration by dry combustion (Nelson & Sommers, 1996). Bulk density for the 0–5 cm and 5–10 cm soil depth was determined by the core method (Blake & Hartge, 1986). The bulk density and soil C and N concentration were used to compute soil total C and total N pool. Soil temperature and moisture of the top 0–5 cm of soil were monitored *in situ* using Stevens Hydraprobe II SDI-12 sensors (Stevens Water Monitoring Systems, Inc., Portland, OR, USA). Sensors were installed to the 5 cm depth in summer 2009 and

Table 3 Amount of stover removed after grain harvest in 2009 through 2011

		% Stover removal				
		0	25	50	75	100
Site	Year	Stover (Mg ha^{-1})				
Colby	2009	0.00	1.35	3.33	4.22	5.27
	2010	0.00	1.88	3.15	4.71	5.86
	2011	0.00	1.77	3.88	6.16	7.61
Hugoton	2009	0.00	1.98	3.04	4.96	5.74
	2010	0.00	1.08	2.81	4.85	4.87
	2011	0.00	2.35	4.91	5.86	8.74
Ottawa	2009	0.00	0.92	2.17	3.26	4.99
	2010	0.00	1.02	1.50	2.24	6.10
	2011	0.00	0.60	1.03	1.61	1.90

remained in place until spring 2011. Sensors were wired to a CR1000 datalogger (Campbell Scientific, Inc., Logan, UT, USA) connected to a solar panel-powered battery and recorded measurements every 60 min. One sensor was installed in each plot.

At maturity, corn grain and stover was hand-harvested from the two center rows of each plot from an area of 1.5 m by 2 m in 2009, 2010, and 2011. As noted earlier, plants were cut with shears leaving 15 cm of stalk above the soil surface to simulate common combine stalk cutting heights. Corn ears and stover were weighed and oven dried at 65 °C for 72 h. Grain mass was adjusted to 155 g kg^{-1} water content for yield comparison.

All data were analyzed using the PROC MIXED feature of SAS 9.2 (SAS Institute, 2008). Runoff depth, sediment, and sediment-associated C data for statistical analysis were transformed using the logarithmic function to achieve normal distribution. Differences among treatments were tested using least squares means at the 0.05 probability level (SAS Institute, 2008). Treatments were compared by site as soil, climate, and management varied among sites.

Results

Water erosion parameters

Stover removal impacts on runoff, sediment, and sediment-associated C loss were significant. Magnitude of removal effects varied, however, with site. Stover removal resulted in increased runoff at Colby (Fig. 2a) but not at Hugoton (Fig. 2b) and Ottawa (Fig. 2c). At Colby, 50% stover removal resulted in increased runoff depth by 11 mm, while 100% removal resulted in increased runoff depth by 17 mm relative to no removal (Fig. 2a). Stover removal had greater impacts on sediment loss than runoff. It caused sediment loss at all sites (Fig. 3a–c). Complete removal resulted in increased sediment loss by about 0.40 Mg ha^{-1} at Colby and Hugoton. At Ottawa, stover removal at rates as low as 50% resulted in increased sediment loss by 0.30 Mg ha^{-1}, while 100% removal resulted in increased sediment loss by about 0.47 Mg ha^{-1}.

Stover removal also caused sediment-associated C loss except at Colby (Fig. 4a). At Hugoton, complete removal resulted in increased sediment-associated C loss by 0.58 kg ha^{-1} (Fig. 4b). At Ottawa, compared with 0% removal, 50% removal resulted in sediment-associated C loss by 0.29 kg ha^{-1}, while 75 and 100% removal resulted in increased sediment-associated C loss by an average of 0.56 kg ha^{-1} (Fig. 4c). Stover removal at high rates also impacted wet aggregate stability expressed as mean weight diameter of aggregates. It reduced mean weight diameter at all sites 1 year after removal (Table 4). Stover removal at 50% reduced mean weight diameter by 1.35 times at Colby compared with no removal. At Hugoton, only complete removal reduced mean weight diameter by 2.36 times, but at Ottawa, 75% removal reduced mean weight diameter by 1.56 times.

At the rainfed site in Ottawa, complete removal consistently reduced mean weight diameter of aggregates in all years, but at the irrigated sites in Colby and Hugoton, effects were not significant after 2 and 3 years of removal. At Ottawa, complete removal reduced mean weight diameter by 1.28 times in spring 2011 and by 2.78 times in spring 2012 compared with no removal. Stover removal had small or no effects on soil total C pool during the 3-year study (Table 4). There were no statistical differences in soil total N concentration and pool (data not shown). Differences in total C pool among stover removal rates were significant only at the rainfed site (Ottawa) in 2011. Two years after removal, at this site, ≥75% removal reduced C pool by 9.2% (1.70 Mg ha^{-1}) in the top 5 cm of soil relative to no removal. Total C decreased with an increase in stover removal at all sites, but means did not differ due to high variability in data (Table 4).

Soil temperature and water content

Stover removal had large and significant effects on soil water content (Table 5) and soil temperature (Fig. 5). Effects were less pronounced in winter than in other seasons. At Colby, stover removal rates of 50 and 100% caused an increase in soil temperature by 2.7 and 4.2 °C in early summer, respectively, compared to no removal (Fig. 5a). Similarly, at Hugoton, stover removal rates of 50 and 100% resulted in increased summer soil temperature by 2.0 and 3.5 °C, respectively, (Fig. 5b). This trend was generally reversed in winter at all sites. At Colby, 100% stover removal decreased soil temperature by 0.43 °C compared to no removal. At Ottawa, soil under plots with 100% stover removal was 6.8 °C warmer in summer and 0.61 °C cooler in winter compared

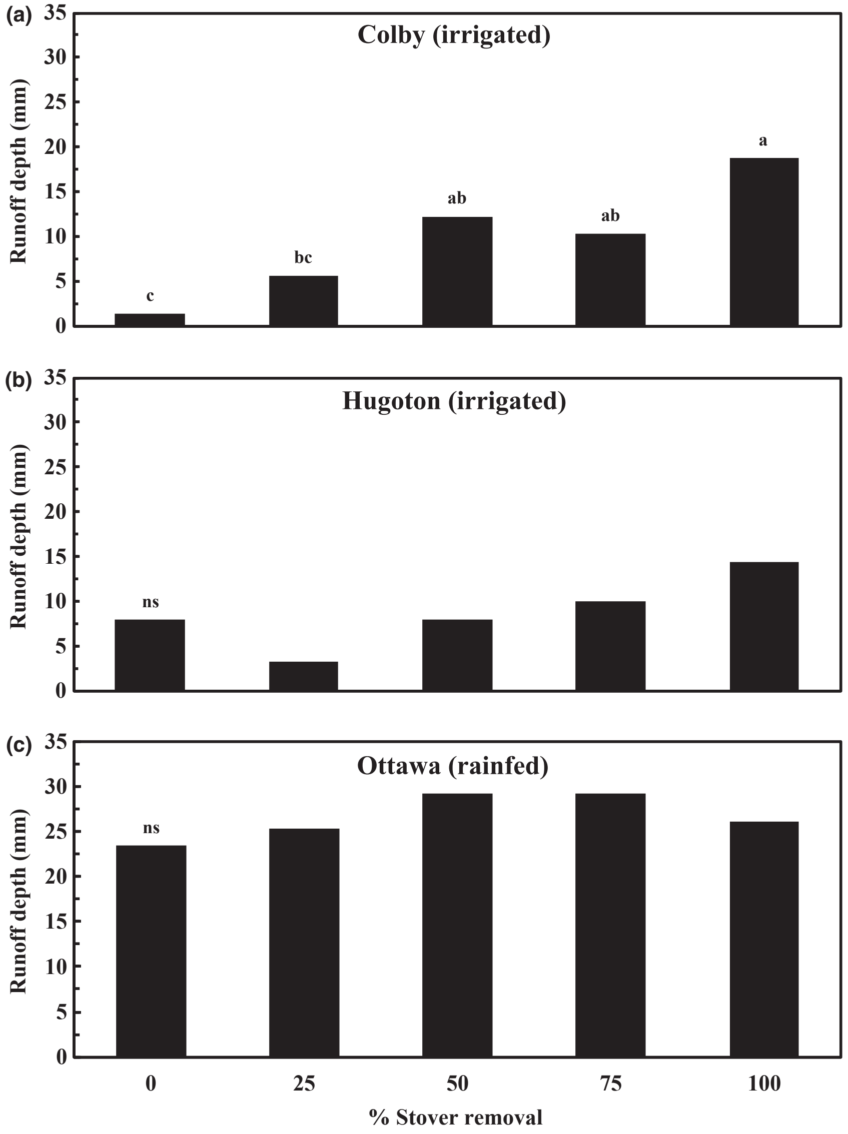

Fig. 2 Impact of stover removal on depth of runoff for (a) Colby, (b) Hugoton, and (c) Ottawa. Treatments within the same site with different letters are significantly different at the 0.05 probability level.

to soil under plots without removal (Fig. 5c). Figure 6 shows the trends in temperature fluctuations for the Colby site between November 2010 and March 2011. It shows that soil temperature under complete stover removal tended to fluctuate more abruptly than under plots without removal. Similar trends in temperature fluctuations were observed for the other two sites (data not shown).

Stover removal had also large impacts on soil water content in the top 5 cm (Table 5). Because impacts of stover removal on soil water content were similar each year, only data for 2010 are reported (Table 5). At all sites, soil water content was generally the lowest when stover was removed. In early summer, removal rates of 50 and 100% reduced soil water content by about 0.07 m^3 m^{-3} compared to no removal. In winter, at this site, 50 and 100% removal rates reduced water content by about 0.04 m^3 m^{-3}. At Hugoton, stover removal reduced water content only in the growing season (May–October). In early summer, 50 and 100% stover removal reduced water content by an average of 0.04 m^3 m^{-3}. In winter, however, water content under 50% was either similar or greater compared to no removal. At Ottawa, in early summer, complete stover removal reduced water content by 0.05 m^3 m^{-3}.

Crop production

The impact of stover removal on grain yield varied with site during the 3-year study (Table 6). At Colby, during

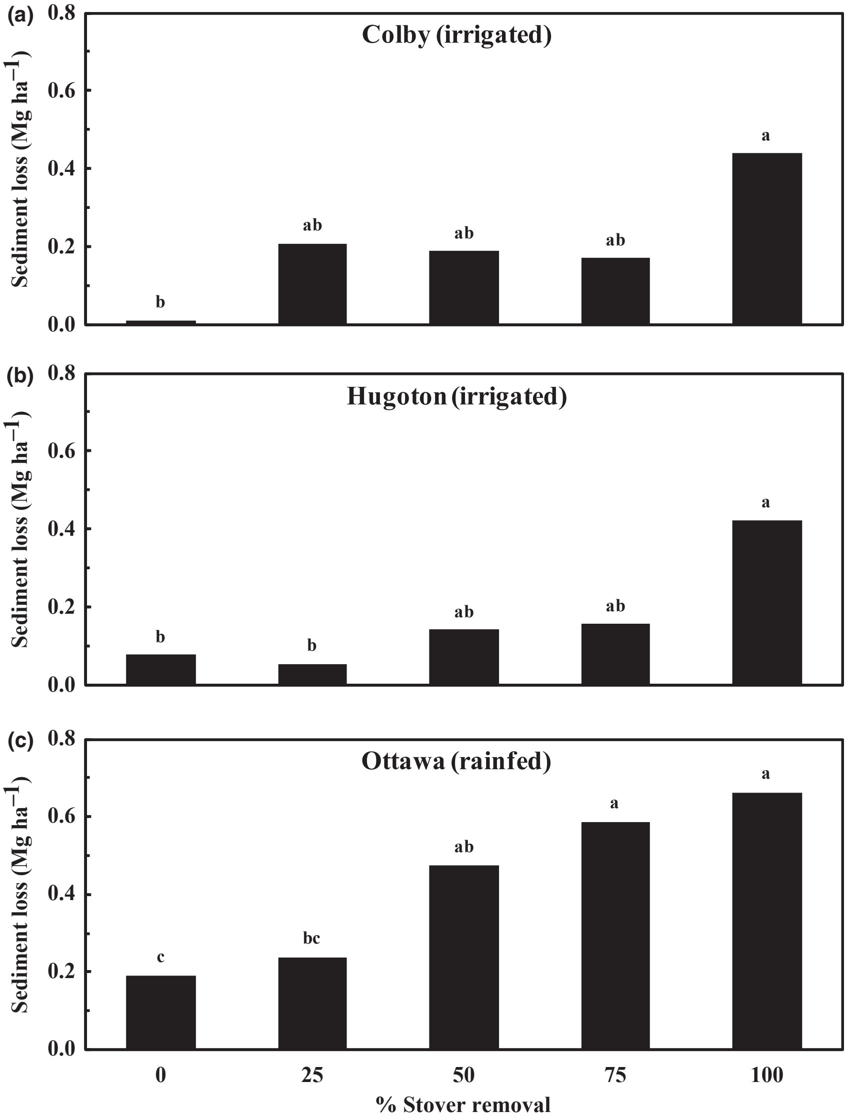

Fig. 3 Impact of stover removal on sediment loss for (a) Colby, (b) Hugoton, and (c) Ottawa. Treatments within the same site with different letters are significantly different at the 0.05 probability level.

the first year after removal (2009), stover removal at 50, 75, and 100% resulted in increased grain yield by 4.75, 5.03, and 4.21 Mg ha^{-1}, respectively, compared with no removal. At Ottawa, for the same year, 100% removal resulted in increased grain yield by 1.94 Mg ha^{-1} relative to no removal. At Colby, in 2010, impact of removal on grain yield was inconsistent. At Ottawa, for the same year, 75 and 100% removal rates resulted in an increase in grain yield by an average of 1.04 Mg ha^{-1} compared to 0 and 25% removal. However, 3 years after removal (2011), differences in grain yield among stover removal treatments were not significant at any of the sites. Similarly, stover yield was not impacted by stover removal rates at Colby or Hugoton in all 3 years (Table 6). At Ottawa, effects were mixed. Complete removal resulted in an increase in stover yield by 1.12 and 3.42 Mg ha^{-1} in 2009 and 2010, respectively, but it reduced stover yield by 0.81 Mg ha^{-1} in 2011 compared with 0% removal.

Discussion

Data from this study in Kansas indicate that stover removal at high rates (>50%) from no-till and strip till soils can, in general, have significant effects on water erosion. The data suggest that intense rainstorms could cause significant loss of sediment and sediment-associated C even in soils with relatively gentle slopes (about 1%) if stover is removed at high rates. Although removal at low rates (≤50%) may not have adverse

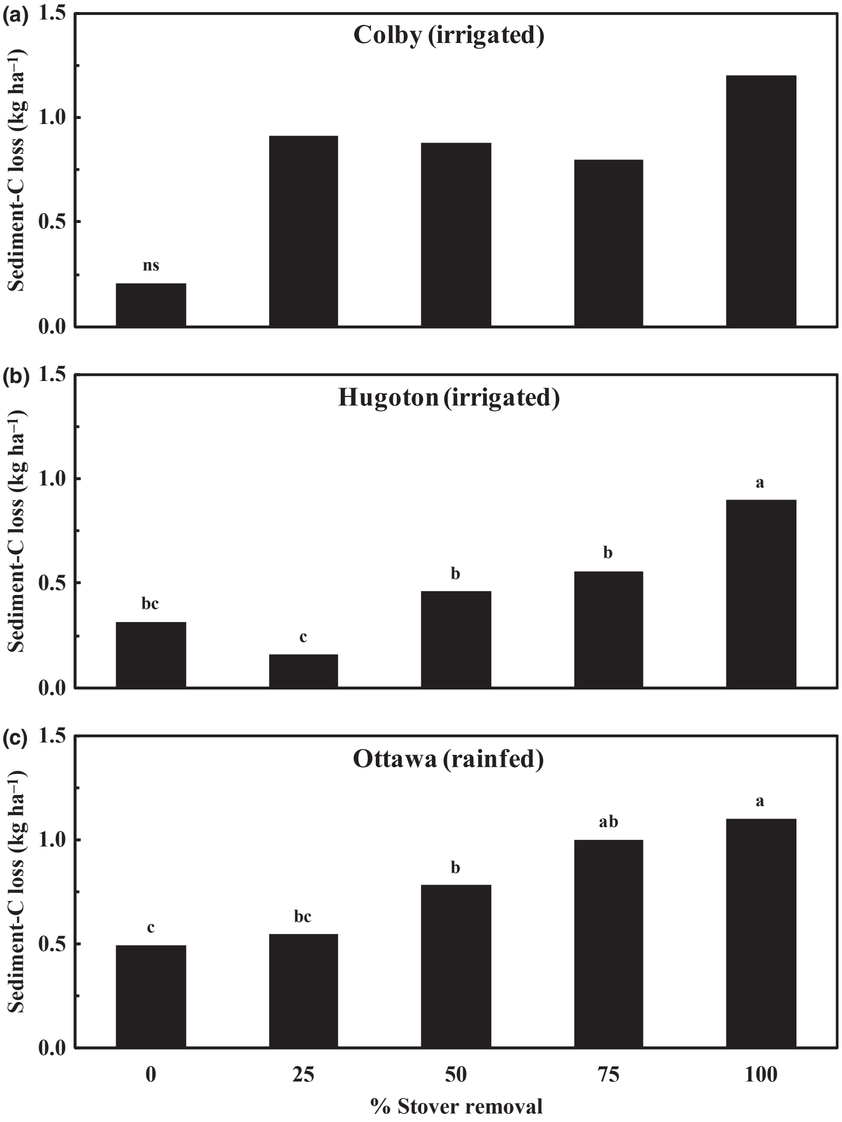

Fig. 4 Impact of stover removal on sediment-C loss for (a) Colby, (b) Hugoton, and (c) Ottawa. Treatments within the same site with different letters are significantly different at the 0.05 probability level.

effects, complete removal can increase sediment loss regardless of soil type and tillage system. Results also indicate that high rates of removal can cause loss of sediment-associated C in runoff.

The amount of sediment loss due to stover removal in this study was, however, smaller compared with that reported in some previous studies (Lindstrom, 1986; Blanco-Canqui *et al.*, 2009). The low sediment loss was probably due to the low intensity of the simulated rainfall and relatively flat soils (<1% slope) at the three sites. Rainfall portraying 5-year return period was applied to each soil to simulate a frequent rainstorms likely to occur shortly after stover removal.

Effects of stover removal on soil erosion parameters appeared to depend on irrigation potential. Stover removal appeared to have larger effects on soils under rainfed than on irrigated conditions. For example, stover removal reduced wet aggregate stability under the rainfed condition (Ottawa) every year, but under irrigated conditions, stover removal resulted in reduced aggregate stability only in the first year. Moreover, removal at rates as low as 50% resulted in increased both sediment and sediment-C loss under the rainfed condition, but under irrigated conditions, only 100% removal increased sediment loss. The greater amount of stover produced with the use of irrigation may explain differences in soil response to stover removal between irrigated and rainfed sites (Table 6).

The reduction in the amount of large water-stable aggregates with stover removal, particularly at the

Table 4 Impact of stover removal on mean weight diameter of water-stable aggregates, bulk density and soil C pool by site and year. Treatments within the same site and year with different letters are significantly different at the 0.05 probability level

		% Stover removal				
Site	Year	0	25	50	75	100
Mean weight diameter (mm)						
Colby	2010	2.17^{a}	2.34^{a}	1.61^{b}	1.77^{b}	1.31^{c}
	2011	2.14	1.65	2.29	1.7	1.31
	2012	1.35	1.72	0.81	0.59	0.91
Hugoton	2010	1.96^{a}	1.48^{ab}	1.57^{ab}	1.45^{ab}	0.83^{b}
	2011	2.57	2.26	2.24	2.37	1.63
	2012	1.90	1.48	1.40	1.12	1.09
Ottawa	2010	1.89^{a}	1.69^{ab}	1.40^{ab}	1.21^{b}	1.27^{b}
	2011	2.06^{a}	2.21^{a}	1.93^{ac}	1.29^{b}	1.61^{bc}
	2012	1.13^{a}	0.57^{ab}	0.57^{ab}	0.55^{ab}	0.41^{b}
Bulk density (Mg m^{-3})						
Colby	2010	1.31	1.26	1.27	1.25	1.30
	2011	1.36	1.39	1.26	1.31	1.38
	2012	1.32	1.30	1.27	1.28	1.32
Hugoton	2010	1.22	1.31	1.23	1.34	1.25
	2011	1.27	1.36	1.28	1.32	1.36
	2012	1.44^{a}	1.45^{a}	1.25^{b}	1.31^{b}	1.22^{b}
Ottawa	2010	1.17	1.23	1.20	1.16	1.24
	2011	1.32	1.31	1.29	1.32	1.31
	2012	1.23^{ab}	1.27^{ab}	1.30^{a}	1.21^{b}	1.29^{ab}
Soil C (Mg ha^{-1})						
Colby	2010	15.4	14.6	14.8	14.9	13.9
	2011	15.7	15.3	15.2	15.3	14.3
	2012	18.3	17.1	17.3	15.5	14.0
Hugoton	2010	11.5	10.2	10.7	10.4	8.18
	2011	10.6	10.8	10.1	10.4	9.52
	2012	14.4	19.8	15.5	9.7	11.1
Ottawa	2010	18.4	18.9	17.7	16.7	16.7
	2011	18.4^{a}	18.0^{ab}	18.1^{a}	16.9^{bc}	16.5^{c}
	2012	17.5	18.5	18.3	16.2	16.5

Table 5 Impact of stover removal on mean monthly soil water content for the 0- to 5-cm depth in 2010. Soil water content data using sensors were measured only in three stover removal treatments (0, 50, and 100%). Dashes represent periods when the sensors were not installed due to frozen soil conditions and field operations that prevented installation. Treatments within the same site and month with different letters are significantly different at the 0.05 probability level

Site	% Stover removal	January	February	March	April	May	June	July	August	September	December
mm^{3} mm^{-3}											
Colby	0	–	–	–	–	–	0.39^{a}	0.38^{a}	0.38^{a}	0.31^{a}	0.12^{a}
	50	–	–	–	–	–	0.31^{c}	0.33^{b}	0.30^{b}	0.21^{b}	0.08^{b}
	100	–	–	–	–	–	0.33^{b}	0.32^{b}	0.30^{b}	0.20^{c}	0.08^{b}
Hugoton	0	0.18^{a}	0.21^{b}	0.23^{b}	0.23^{b}	0.29^{a}	0.27^{a}	0.34^{a}	0.34^{a}	0.21^{a}	–
	50	0.19^{a}	0.25^{a}	0.29^{a}	0.29^{a}	0.25^{b}	0.23^{b}	0.29^{c}	0.31^{b}	0.18^{b}	–
	100	0.16^{b}	0.19^{c}	0.24^{b}	0.24^{b}	0.25^{b}	0.23^{b}	0.30^{b}	0.33^{a}	0.19^{b}	–
Ottawa	0	0.39^{a}	0.33^{a}	0.43^{a}	0.39^{a}	–	0.30^{a}	0.33^{a}	0.21^{a}	0.31^{b}	0.22^{a}
	50	0.32^{b}	0.27^{b}	0.38^{ab}	0.30^{b}	–	0.29^{a}	0.33^{a}	0.23^{a}	0.37^{a}	0.22^{a}
	100	0.30^{b}	0.27^{b}	0.37^{b}	0.29^{b}	–	0.25^{b}	0.29^{b}	0.18^{b}	0.31^{b}	0.18^{b}

rainfed site, suggests that soil structural stability may decrease if stover is removed at high rates. Soil aggregate stability appeared to be more responsive to stover removal than total soil C. Stover removal reduced soil C pool at the Ottawa site in the second year where the total C decreased by 1.5 Mg ha^{-1} with 75% removal, closely

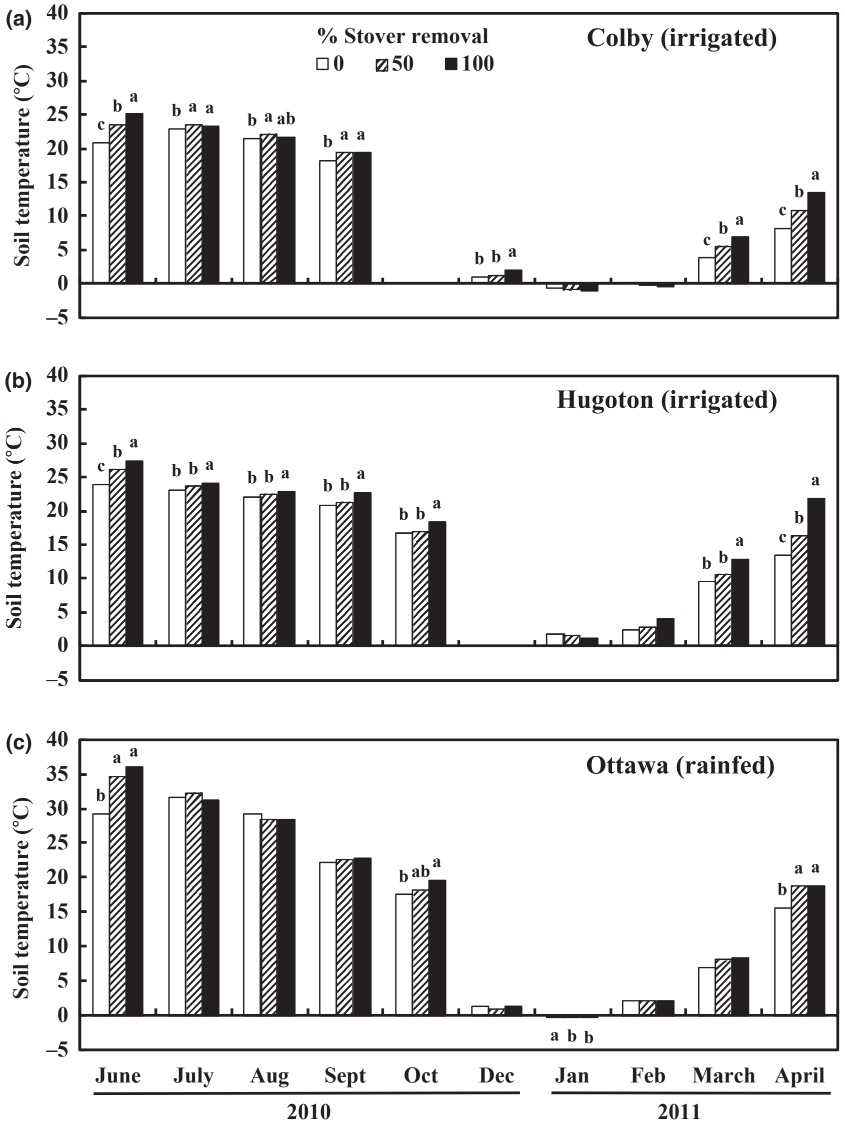

Fig. 5 Effects of stover removal on mean monthly midday soil temperature of the top 5 cm for (a) Colby, (b) Hugoton, and (c) Ottawa. Treatments within the same site with different letters are significantly different at the 0.05 probability level. Bars not followed for letters are not significantly different. Sensors data were not available for October at Colby and December for Hugoton.

resembling the 1.95 Mg ha^{-1} decrease observed under 75% stover removal in a sloping silt loam in Ohio (Blanco-Canqui & Lal, 2007). This decrease in soil C pool probably contributed to the reduced wet aggregate stability with stover removal at this site. Soil organic matter binds soil particles together and enhances soil aggregation (Six *et al.*, 2006).

Results indicated that stover removal may not rapidly affect total soil C. In this study, however, we measured only total C. Recent studies have suggested that stover removal may more rapidly affect labile C fractions than total C (Neill, 2011; Hammerbeck *et al.*, 2012). Assessment of different soil C fractions under stover removal is needed to better understand soil C dynamics shortly after removal. It is important to note that although there were no statistical differences in total C at any site after 3 years, Table 4 shows a consistent decrease in soil C with an increase in stover removal at all sites. On the basis of this consistent trend, we hypothesize that total soil C could significantly decrease in these soils in the long term if stover is removed at high rates annually.

As expected, stover removal altered the soil temperature. Soils without stover removal were generally cooler in the summer months and warmer in the winter months compared with 50 and 100% removal at all study sites (Fig. 5). The considerable fluctuations in soil temperature due to stover removal, shown in Fig. 6, agree with

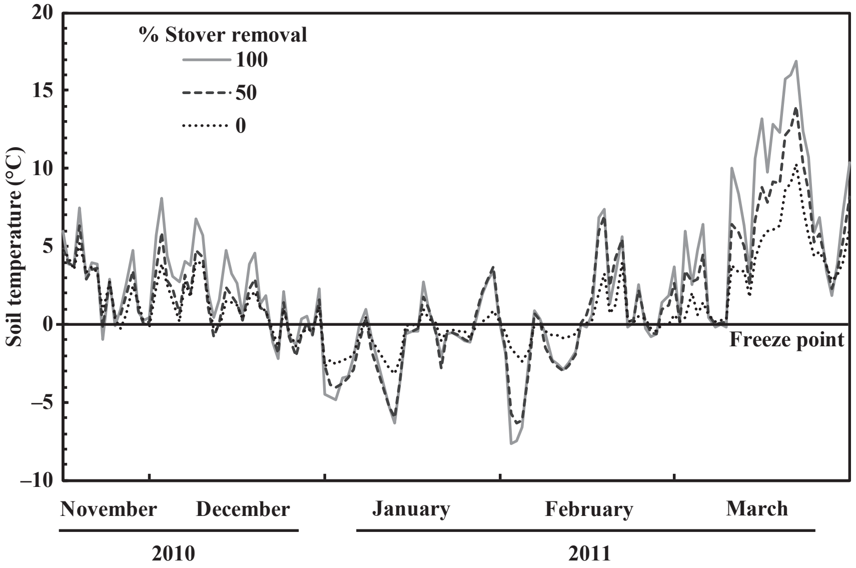

Fig. 6 Effects of stover removal on freeze–thaw cycles at 5 cm throughout the 2010–2011 winter season at Colby. Sensors were not installed during the 2009–2010 winter season.

Table 6 Impact of stover removal on corn grain and stover yield in 2009, 2010, and 2011. Treatments within the same site and year with different letters are significantly different

		% Stover removal				
Site	Year	0	25	50	75	100
Grain yield (Mg ha^{-1})						
Colby	2009	13.11^{b}	16.48^{ab}	17.86^{a}	18.14^{a}	17.32^{a}
	2010	14.07^{ab}	14.72^{ab}	16.42^{a}	14.36^{ab}	12.42^{b}
	2011	6.73	8.81	9.42	8.91	9.99
Hugoton	2009	11.10	11.94	11.87	12.54	10.50
	2010	15.78	15.14	16.79	16.07	15.51
	2011	12.22	10.83	13.00	10.76	14.07
Ottawa	2009	7.49^{bc}	6.32^{c}	7.96^{ab}	8.08^{ab}	9.43^{a}
	2010	4.40^{c}	4.40^{c}	4.58^{abc}	5.55^{a}	5.33^{ab}
	2011	0.88	1.05	1.23	1.58	1.40
Stover yield (Mg ha^{-1})						
Colby	2009	5.68	5.40	6.65	5.63	5.27
	2010	6.24	7.53	6.30	6.28	5.86
	2011	7.28	7.08	7.76	8.21	7.61
Hugoton	2009	7.05	7.90	6.08	6.61	5.74
	2010	6.58	4.33	5.61	6.47	4.87
	2011	9.66	9.40	9.81	7.81	8.74
Ottawa	2009	3.87^{b}	3.66^{b}	4.34^{ab}	4.35^{ab}	4.99^{a}
	2010	2.68^{b}	4.07^{ab}	3.00^{b}	2.98^{b}	6.10^{a}
	2011	2.71^{a}	2.41^{ab}	2.05^{ab}	2.14^{ab}	1.90^{b}

the findings of Sharratt (2002) and may result in more freeze–thaw events on soils with 50 and 100% stover removal, increasing breakdown of soil aggregates (Mostaghimi *et al*., 1988). Results also indicate that stover removal at rates of 50% can reduce soil water content (Table 5). The reduced soil temperature in mulched plots probably reduced evaporation, thereby increasing soil water content (Table 5). The greater water content under mulched soils may benefit crops and reduce irrigation water requirements. It can also reduce soil temperature fluctuations due to the high specific heat capacity of water.

The increase in grain yield at two sites in the first and second year may be attributed to the slow soil warming in spring in mulched plots, which probably impaired germination and early root growth, lowering grain yield (Table 6). In this study, germination rate was not, however, monitored. In spring, soil temperature in plots with 100% removal was higher than in plots with no stover removed (Fig. 5). The significant differences in grain yield after stover removal in the first 2 years at two sites and lack of differences at all sites after 3 years indicate that stover removal impacts on grain yield can be variable from year to year, suggesting the need for long-term monitoring of stover removal impacts. The lack of differences in grain yield among stover treatments at the Hugoton site suggests that effects of stover on grain yield are soil and management-specific. The soil at the Hugoton site is loam while the soils at Colby and Ottawa are silt loam. In addition, strip tillage was used on the loamy soil and no-till management on the silt loams. Results appear to suggest that stover mulch may tend to reduce grain yield in no-till but not on strip till management where stover-free strips are created during planting.

The grain yield at the rainfed site (Ottawa) was lower than under irrigated conditions (Table 6). This was particularly large in the last 2 years attributed to increased severe weather fluctuations, which reduced both grain and stover yields in rainfed corn. In 2010, the reduced grain and stover yields at Ottawa were the result of wet saturated soil and high temperatures in May. In 2011, the reduced yields were due to the severe drought conditions in the region. Table 2 shows that rainfall amount at the Ottawa site between June and September in 2011 was only 51% of the 10-average and 54% of the 30-year average. For the same year, under irrigated condition at Hugoton, rainfall amount between June and September was only 67% of the long-term averages. These results indicate that precipitation input and use of irrigation water can significantly influence the extent at which stover removal impacts corn yields.

This study under rainfed and irrigated conditions indicates that corn stover removal had significant effects on soil water erodibility parameters and small or no effects on crop yields across three soils in Kansas. Stover removal at rates <50% may not significantly increase water erosion in these relatively flat soils, but complete stover removal could increase water erosion in all soils. Rainfall in semiarid regions often occurs in the form of localized and intense rainstorms, particularly under increasing climatic fluctuations, which may increase risks of water erosion if stover is excessively removed. Stover removal appears to have more negative effects on soil properties in rainfed than in irrigated soils due to lower stover production in rainfed conditions. For example, soil aggregate stability, an essential indicator of soil structural stability, decreased in all years in the rainfed but not in irrigated sites. The small positive or no effect of stover removal on grain yield is promising as it indicates that stover removal may not decrease grain yield in the short term. Any increase in grain yield with stover removal should be, however, weighed against the adverse impacts of stover removal on water erosion, soil aggregate stability, and changes in soil water content and soil temperature regimes, which are critical to maintain the soil resource base for agricultural production. Further monitoring of soil and crop response to stover removal is needed to determine long-term effects and establish threshold levels of stover removal in both rainfed and irrigated conditions.

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