Cover Crops Could Offset Crop Residue Removal Effects on Soil Carbon and Other Properties: A Review

Sabrina J. Ruis* and Humberto Blanco-Canqui

ABSTRACT

Crop residue removal for livestock or biofuel production is common. Excessive residue removal may reduce soil organic carbon (SOC) and other soil properties. Cover crop (CC) could be a strategy to ameliorate negative effects of residue removal, but this has not been widely discussed. We synthesized studies on the impacts of CC addition following crop residue removal on SOC and related properties, discussed opportunities and challenges of using CC after residue removal, and highlighted research needs. We first briefly reviewed the separate effects of residue removal and CC before reviewing their combined effects. Our review found that ≥50% residue removal reduced SOC stocks by 0.87 Mg ha^{-1} yr^{-1} and <50% removal by 0.31 Mg ha^{-1} yr^{-1}. However, CC increased SOC by 0.49 Mg ha^{-1} yr^{-1}, suggesting that CC could offset at least part of the SOC lost with removal. Studies evaluating CC effects on soil properties after residue removal are few and short term (<6 yr) but appeared to show limited potential of CC to offset residue removal effects. However, some studies indicated trends for increased SOC, suggesting CC may offset removal effects in the long term. While opportunities exist to integrate residue removal with CC use, challenges including low CC biomass and reduction in crop yield in water-limited regions must be addressed. Further research on interactive effects of CC and residue removal is needed across different cropping systems and climates.

Core Ideas

- Corn residue removal reduces soil organic C stocks and other soil properties.
- Cover crop increases soil organic C stocks and other properties.
- Cover crop may not offset soil organic C losses from residue removal in the short term.
- More data are needed on cover crop effects on soil properties after residue removal.

Removal of crop residue for animal feed, bedding, and biofuel production is an increasingly common practice in the United States (Liska et al., 2014; Blanco-Canqui et al., 2016a; Blanco-Canqui et al., 2016b). Crop residue removal may occur through grazing or mechanical means such as baling. Approximately 59.3 million ha were planted to corn (*Zea mays* L.) and small grains in 2015, (USDA-NASS, 2016). This resulted in 296 to 593 million Mg of residue or straw available for harvest assuming residue or straw yields of 5 to 10 Mg ha^{-1}. Crop residues, such as corn stover, are considered an inexpensive source of feedstocks and bedding.

The concern with crop residue removal is that it may negatively impact soil processes and properties especially when residue is removed at high rates such as through baling. Excessive crop residue removal could reduce SOC, increase risks of water and wind erosion, and reduce soil fertility, biology, and productivity, among others. Leaving crop residue on the soil surface or incorporating crop residue after harvest contributes to the maintenance or accumulation of organic C in the soil. However, removal of residue may reduce SOC stocks and negatively affect related soil properties. Soil organic C directly influences soil biological, chemical, and physical properties, which affect soil productivity and environmental quality. For example, an increase in SOC improves soil aggregate stability (van Groenigen et al., 2011; Blanco-Canqui et al., 2013; Laird and Chang, 2013; Tian et al., 2014; Villamil et al., 2015; Kenney et al., 2015; Johnson et al., 2016), which reduces the susceptibility of soil to wind erosion (Blanco-Canqui et al., 2014, 2016b; Tian et al., 2014; Nelson et al., 2015; Jin et al., 2015; Johnson et al., 2016) and water erosion (Beniston et al., 2015; Kenney et al., 2015).

A strategy to reduce the residue removal-induced losses of SOC and degradation of soil properties could be the use of CC following crop residue removal. Cover crop could provide additional biomass C input and soil cover when fields would otherwise be bare, leading to improved soil properties. It is, however, important to understand the extent to which CC addition influences SOC stocks and other soil properties after crop residue removal. Similarly, a further understanding of crop residue removal effects on SOC is needed as such effects can depend on management duration, soil texture, tillage, climate, cropping system, and CC species. Some previous reviews have discussed changes in SOC stocks under residue removal (Blanco-Canqui and Lal, 2009; Smith et al., 2012; Raffa et al., 2015) and CC

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5585 Guilford Road, Madison, WI 53711 USA

Dep. of Agronomy and Horticulture, Univ. of Nebraska-Lincoln, Lincoln, NE 68583. Received 23 Nov. 2016. Accepted 26 Mar. 2017.
*Corresponding author (sruis2@unl.edu).

Abbreviations: CC, cover crop; FDA, fluorescein diacetate method; POM, particulate organic matter; SOC, soil organic carbon.

(Blanco-Canqui et al., 2015), but a review specifically discussing the interactive effects of crop residue removal and CC on SOC and related soil attributes is not available. The objectives of this review were to: (i) synthesize and discuss published studies on the impacts of CC addition following crop residue removal on SOC and related soil properties, (ii) discuss the opportunities and challenges of using CC following residue removal, and (iii) highlight any research needs for the potential combination of the above practices.

Prior to discussing crop residue removal and CC interactions, it is important to briefly review in separate the (i) mechanisms of C cycling, (ii) effects of crop residue removal on SOC and related soil physical, chemical, and biological properties, and (iii) effects of CC alone on the above soil properties. This can allow a better understanding of the processes and extent to which removal of crop residues or addition of CC can affect SOC and other properties and infer how their combination can work under different management conditions.

MECHANISMS OF SOIL CARBON CYCLING UNDER RESIDUE REMOVAL AND COVER CROPS

Stabilization or protection of C in the soil occurs through three general mechanisms: chemical, biochemical, and physical (Six et al., 2002). Chemical protection of SOC occurs through the formation of various types of bonds between fine soil particles and soil organic matter (organo-mineral associations) (Six et al., 2002; Blanco-Canqui and Lal, 2004). Biochemical protection of SOC occurs through the complexity of the organic compounds such as lignin, hemicellulose, and others (Six et al., 2002). Physical protection of SOC occurs through formation of stable soil aggregates, which limits organic matter decomposition and SOC turnover (Six et al., 2002). The ability of soil aggregates to protect SOC depends on aggregate stability and size. Stable microaggregates (<250 μm) can protect SOC more strongly than macroaggregates (>250 μm) (Blanco-Canqui and Lal, 2004). Presence of stable microaggregates is critical for the physical protection of SOC (Six et al., 2002; Blanco-Canqui and Lal, 2004). Removal of residues can reduce soil aggregate stability and result in increased loss of SOC (Blanco-Canqui and Lal, 2009), while CC can contribute to aggregate formation and stabilization through addition of SOC (Blanco-Canqui et al., 2015).

Individual SOC pools, such as organo-mineral associations, may saturate with SOC (Stewart et al., 2008). The difference between saturation and current C concentration is termed saturation deficit (Stewart et al., 2007). Some systems are unable to achieve saturation due to management but have stabilized the maximum C possible under that management. Such soils are said to be at an effective stabilization capacity (Stewart et al., 2007). As an example, conventionally tilled systems have a lower effective stabilization capacity than no-till systems (Stewart et al., 2007). Based on this concept, crop residue removal can initially decrease SOC before achieving a new effective capacity (Fig. 1). In contrast, CC can initially increase SOC before reaching a new effective stabilization capacity (Fig. 1).

RESIDUE REMOVAL EFFECTS ON SOIL PROPERTIES

Reviews on SOC and crop residue removal across different soil types, tillage systems, and climates have reported that residue removal can significantly reduce SOC concentration and stocks (Blanco-Canqui and Lal, 2009; Smith et al., 2012; Raffa et al., 2015). The reviews have also reported that there is significant site-to-site variability. The effect of residue removal on SOC depends on the amount of residue removed. High rates (>50%) of residue removal generally reduce SOC concentration, particularly in the long term (Blanco-Canqui and Lal, 2009). Soil organic C concentration losses with residue removal can range from 15 to 50% when crop residue is removed at rates more

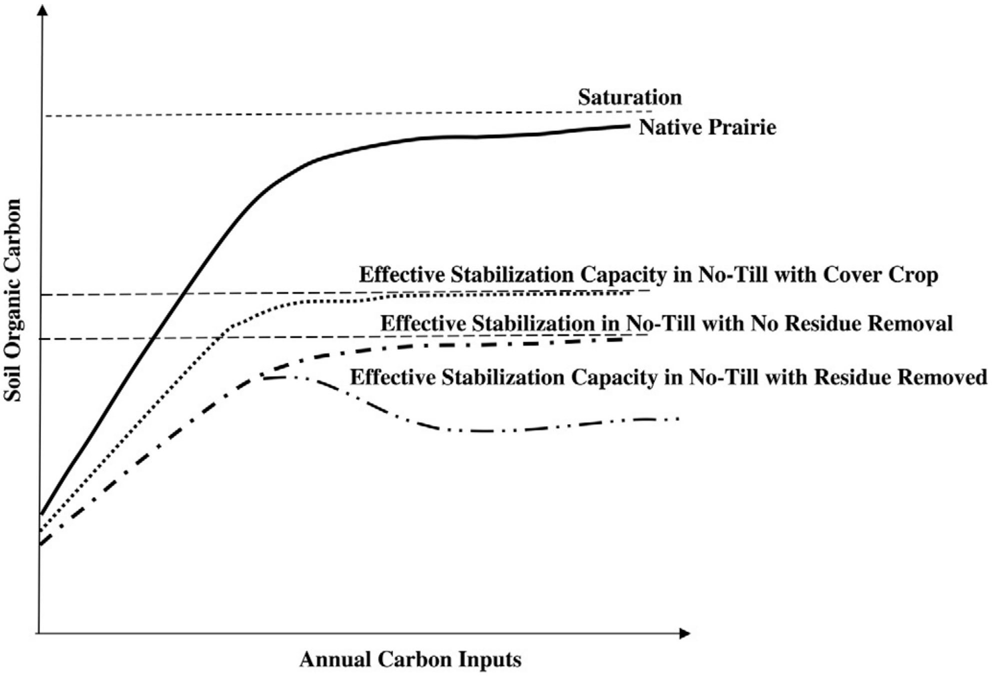

Fig. 1. Effective stabilization capacity of soil organic carbon (SOC) under no-till systems with and without cover crop or residue removal as compared to native prairie (modified from Stewart et al., 2007).

than 50% (Blanco-Canqui and Lal, 2009; Raffa et al., 2015). It was estimated that for every 1 Mg ha^{-1} of residue removed, 0.46 g kg^{-1} of SOC was lost (Blanco-Canqui and Lal, 2009). Using measured and modeled data, Smith et al. (2012) found that for every 1 Mg ha^{-1} of residue removed, 0.21 Mg ha^{-1} of SOC was lost. Based on the data presented by Blanco-Canqui and Lal (2009) and Smith et al. (2012), the rate of SOC loss was about 0.31 Mg ha^{-1} yr^{-1} under <50% residue removal and 0.87 Mg ha^{-1} yr^{-1} under ≥50% residue removal rates. These rates were the difference between no residue removal and residue removal divided by the number of years under residue removal.

Crop residue removal reduced SOC through a number of processes. First, crop residue removal reduces SOC directly through removal of C with the aboveground biomass. Second, high rates of crop residue removal increase water and wind erosion potential, which can potentially increase SOC losses with sediment (Kenney et al., 2015; Blanco-Canqui et al., 2016a; Blanco-Canqui et al., 2016b). Third, residue removal degrades soil structure and reduces soil aggregate size, which accelerates SOC turnover (Six et al., 2000). Fourth, reductions in new substrates for microbes due to residue removal result in microbes using older or less energy efficient C sources for energy, resulting in further loss of SOC (Stetson et al., 2012).

Losses of SOC stock or concentration following residue removal can vary depending on a number of factors: duration of residue removal, soil texture, climate, and others. For example, at two sites in Canada, Malhi et al. (2011a) and Malhi et al. (2011b) measured SOC stock change after 11, 19, and 28 yr of residue removal and found that the extent of losses in SOC stocks due to residue removal tended to increase with time at one site and decrease at another site. Based on these studies, duration under residue removal appears to have mixed effects on SOC stocks. However, studies evaluating effects of duration of residue removal on SOC are very limited to make definitive conclusions.

Soil textural class is another factor that could influence residue removal effects on SOC concentration. Raffa et al. (2015) found that residue removal was more detrimental to SOC concentration in coarse tropical soils, but in temperate environments, soil texture was less important. Regarding climate effects, Raffa et al. (2015) compared the effect of residue removal on SOC in temperate and tropical regions and reported that residue removal in tropical soils resulted in 6% greater losses of SOC than in temperate soils.

Residue removal not only affects SOC concentration but also other soil properties. For example, removal of residue at rates above 50% reduces amount of water-stable aggregates (Blanco-Canqui and Lal, 2009). The reduction in the amount of water-stable aggregates can increase risks of water erosion. Similarly, high rates of residue removal can increase wind erosion potential by reducing dry aggregate size and stability (Osborne et al., 2014; Blanco-Canqui et al., 2016b). The decline in soil aggregation results in lower total porosity and water infiltration (Blanco-Canqui and Lal, 2009). Residue removal can also reduce soil fertility including soil N, P, and K concentrations. Finally, residue removal can reduce soil biota, which adversely affects SOC, nutrient cycling, and soil aggregation (Lehman et al., 2014). Overall, crop residue removal, particularly at high rates, can be detrimental to SOC concentrations as well as other soil properties.

COVER CROP EFFECTS ON SOIL PROPERTIES

Reviews on SOC and CC across different soil types, tillage systems, and climates have reported that CC can significantly increase SOC stocks from 0 to 3.50 Mg ha^{-1} yr^{-1} (Blanco-Canqui et al., 2015; Poeplau and Don, 2015). This wide range in SOC accumulation indicates that CC effects on SOC can be highly variable. Based on Tables 1 and 2, the average rate of SOC increase was 0.45 g kg^{-1} yr^{-1} for SOC concentration and 0.49 Mg ha^{-1} yr^{-1} for SOC stocks in the upper 30 cm of the soil. The difference in SOC gain between SOC concentration and SOC stocks with CC was likely due to differences in soil bulk density. Cover crops can increase SOC by adding biomass C input, improving soil aggregation to protect SOC (McVay et al., 1989; Villamil et al., 2006; Blanco-Canqui et al., 2015), and decreasing water and wind erosion potential, which also cause losses of SOC (De Baets et al., 2011; Blanco-Canqui et al., 2015).

Time after CC establishment, soil texture, CC species, tillage, and climate can be some of the factors influencing CC effects on SOC (Fig. 2). Cover crop effects on SOC are generally not detected in the first few years after establishment; however, SOC stocks can significantly increase (0.32 Mg ha^{-1} yr^{-1}) with time (Blanco-Canqui et al., 2015; Poeplau and Don, 2015). Soil textures with greater clay content or those with low initial C concentration may increase in SOC more readily than sandy soils or those with high initial C concentration (Blanco-Canqui et al., 2015). Other categorical variables such as CC species (legume, grass or non-legume, or mixes), tillage (no-till vs. tillage), and climate (tropical vs. temperate) appear to show no effects on SOC (Poeplau and Don, 2015).

We expanded the dataset of Poeplau and Don (2015) to explore the interactive effects of CC and tillage, precipitation, temperature, CC species, and years under CC management on SOC concentration and stocks from 30 studies to a total of 47 studies. Across all years, SOC concentration gain with CC was not correlated with duration ($r = 0.16$; $P > 0.05$; $n = 79$). However, the rate of SOC stock gain with CC was moderately and linearly correlated with duration ($r = 0.51$; $P < 0.001$; $n = 71$; Fig. 3). This indicated that the longer a field is under CC, the greater the SOC gain. The correlation between duration and SOC stock gain under CC explained only about 21% of the variability in SOC stock gain under CC. This correlation between SOC stock gain under CC with duration was similar to that reported by Poeplau and Don (2015). Our findings indicate that the potential of CC to increase SOC stocks increases with time following establishment.

Within a tillage regime, there was significant variability in SOC response to CC use. Mean annual SOC concentration gain was 0.49 ± 0.35 g kg^{-1} yr^{-1} for no-till, 0.11 ± 0.09 g kg^{-1} yr^{-1} for conventional till, and 0.47 ± 0.52 g kg^{-1} yr^{-1} for other tillage practices (Table 1). These data indicate that tillage does not affect SOC gain under CC. Mean annual SOC stock gain was 0.54 ± 0.17 for no-till, 0.29 ± 0.05 Mg ha^{-1} yr^{-1} for chisel plow, and 0.77 ± 0.27 Mg ha^{-1} yr^{-1} for conventional till (Table 2). These data indicate that CC do not accumulate SOC stocks at different rates under different tillage systems. No-till, chisel plow, and conventional till were similar in rate of SOC stock gain under CC.

Table 1. Cover crop (CC) effects on rate of soil organic carbon concentration (SOC) gain in different locations, climates, soil textural classes, cover crop species, and duration of cover crops. MAP = Mean annual precipitation, MAT = mean annual temperature, NT = no-till, CT = conventional till, MB = moldboard plow, na = data were not available, conc = concentration. Means followed by the same lowercase letter within the same study location are not significantly different. Studies are divided into those that documented an increase in SOC and those that documented no change in SOC.

Location	MAP	MAT	Soil texture, initial SOC	Tillage	Crop	Cover crop	Duration	Depth	SOC conc.	SOC gain	Reference
	mm	°C					yr	cm	g kg^{-1}	g kg^{-1} yr^{-1}	
						Cover crop increased soil organic C concentration					
India	400	28.3	Sandy loam, 4.32 g kg^{-1}	Tilled	Pearl millet (*Pennisetum glaucum* L.)–wheat (*Triticum aestivum* L.)	No CC	6	0–15	4.83b		Chander et al., 1997
						Cow pea (*Vigna unguiculata* L.)			4.78b	–0.0083	
						Prickly sebania (*Sesbania aculeata*)			5.37a	0.09	
India	400	28.3	Sandy loam, 4.2 g kg^{-1}	Tilled	Pearl millet–wheat	No CC	11	0–15	5.8b		Goyal et al., 1999
						Prickly sebania (*Sesbania bispinosa*)			6.2a	0.04	
Garden City, KS	489	12.1	Silt loam, 9.1 g kg^{-1}	NT	Winter wheat	No CC	5	0–7.5	8.7d		Blanco-Canqui et al., 2013
						Winter lentil (*Lens culinaris* Medik)			9.2cd	–0.10	
						Spring pea (*Pisum sativum* L.)			10.1bcd	0.28	
						Spring lentil			10.8bc	0.42	
						Winter triticale (× *Triticosecale* Wittm. ex A. Camus.)			11.4bc	0.54	
						Spring triticale			11.6ab	0.58	
						Winter wheat			13.0a	0.86	
Poland	540	7.6	Sandy, 9.82 g kg^{-1}	Plowed	Soybean (*Glycine max* L.)–winter wheat–sugarbeet (*Beta vulgaris* L.)	No CC	3	0–15	9.13b		Harasim et al., 2016
						Rye (*Secale cereale* L.)			10.29a	0.39	
						Oilseed rape (*Brassica napus* L.)			10.00a	0.29	
						White mustard (*Sinapis alba* L.)			10.58a	0.48	
Denmark	626	7.8	Sandy loam, na	MB	Barley (*Hordeum vulgare* L.)–potato (*Solanum tuberosum* L.)–winter wheat	No CC	12	0–25	na		Schjønning et al., 2012
						Clover (*Trifolium* sp.) or faba bean (*Vicia faba* L.)			na	0.057	
India	710	25.5	Clay loam, 4.83 g kg^{-1}	Disk	Rice (*Oryza sativa* L.)–wheat	No CC	2	0–15	5.08b		Mandal et al., 2003
						Sesbania (*Sesbania rostrata*)			5.99a	0.45	
						Prickly sesbania (*Sesbania aculeata*)			5.78a	0.35	
Canada	817	4.5	Silt loam, 24.0 g kg^{-1}	Disk	Barley–wheat	No CC	4	0–20	16.0b		N'Dayegamiye and Tran, 2001
						Clover			15.0c	–0.25	
						Millet			20.0a	1.0	
						Buckwheat (*Fagopyrum esculentum* Moench)			19.0a	0.75	
						Colza (*Brassica campestris* L.)			22.0a	1.50	
						Mustard (*Brassica campestris* Moench)			23.0a	1.75	

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Table 1 (continued).

Location	MAP	MAT	Soil texture, initial SOC	Tillage	Crop	Cover crop	Duration	Depth	SOC conc.	SOC gain	Reference
	mm	°C					yr	cm	g kg^{-1}	g kg^{-1} yr^{-1}	
Italy	826	15.0	Loam, 10.5 g kg^{-1}	Across tillage systems	Corn–wheat–sunflower (*Helianthus* sp.)	No CC	15	0–10	15.41b		Sapkota et al., 2012
						Hairy vetch (*Vicia villosa* L.)			15.34b	−0.005	
						Mustard (*Brassica juncea* L.)			17.21a	0.12	
Argentina	1019	17.5	Silt loam, 16.6 g kg^{-1}	NT	Soybean	No CC	6	0–5	19.4c		Duval et al., 2016
						Wheat			25.5a	1.02	
						Oat (*Avena sativa* L.)			24.3a	0.82	
						Oat–vetch (*Vicia sativa* L.)			24.5a	0.85	
						Vetch			22.5b	0.52	
Urbana, IL	1045	10.9	Silt loam, na	NT	Corn–soybean	No CC	5	0–30	20.34a		Villamil et al., 2006
						Hairy vetch–rye			22.09b	0.35	
						Rye			20.93a	0.12	
Tifton, GA	1192	18.6	Loamy sand, na	Conservation tillage	Sweet corn	No CC	4	0–7.6	4.69c		Hubbard et al., 2013§
						Sunn hemp (*Crotalaria juncea* L.)			7.24a	0.64	
						Crimson clover (*Trifolium incarnatum* L.)			5.48b	0.20	
						Sunn hemp–crimson clover			7.25a	0.64	
Griffin, GA	1197	16.4	Sandy loam, 11.3 g kg^{-1}	NT	Sorghum (*Sorghum bicolor* L.)	No CC	3	0–7.5	7.9b		Hargrove, 1986
						Rye			8.7b	0.27	
						Crimson clover			8.4b	0.17	
						Subterranean clover (*Trifolium subterraneum* L.)			10.0a	0.70	
						Hairy vetch			9.7a	0.60	
						Common vetch			10.2a	0.77	
Coastal Plain, GA	1219	19.3	Sandy clay loam, na	NT	Sorghum	No CC	3	0–5	8.5c		McVay et al., 1989
						Wheat			8.9c	0.13	
						Crimson clover			10.6a	0.70	
						Hairy vetch			10.2b	0.57	
Japan	1250	13.0	Loam, na	Tilled	Rice	No CC	13	na	13.6b		Ishikawa, 1988
						Milk vetch (*Astragalus onobrychis* L.)			18.7a	0.39	
Japan	1250	13.0	Loam, na	Tilled	Rice	No CC	54	na	21.7b		Ishikawa, 1988
						Milk vetch			28.9a	0.13	
Limestone Valley, GA	1360	15.0	Clay loam, na	NT	Corn	No CC	3	0–5	10.1b		McVay et al., 1989
						Wheat			11.8a	0.57	
						Crimson clover			12.8a	0.90	
						Hairy vetch			11.8a	0.57	

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Table 1 (continued).

Location	MAP	MAT	Soil texture, initial SOC	Tillage	Crop	Cover crop	Duration	Depth	SOC conc.	SOC gain	Reference
	mm	°C					yr	cm	g kg^{-1}	g kg^{-1} yr^{-1}	
Milan, TN	1368	14.9	Silt loam, na	NT	Corn	No CC†	11	0–5	10.0c		Mullen et al., 1998
						No CC‡			12.5b		
						Hairy vetch†			14.7ab	0.43	
						Hairy vetch‡			15.0a	0.23	
						Wheat†			10.2bc	–0.02	
						Wheat‡			15.4a	0.26	
Belle Mina, AL	1551	15.2	Silt loam, 8.54 g kg^{-1}	Across tillage systems	Cotton (*Gossypium hirsutum* L.)	No CC	3	0–15	10.47b		Nyakatawa et al., 2001
						Rye			12.79a	0.77	
Brazil	1947	17.1	Clay, 19.0 g kg^{-1}	CT	Corn–soybean	No CC	23	0–5	24.6b		Balota et al., 2014
						Black oat (*Avena strigosa* Schreb.)			27.7b	0.13	
						Winter wheat			25.2b	0.03	
						Oilseed radish (*Raphanus sativus* L.)			25.5b	0.04	
						Blue lupin (*Lupinus angustifolius* L.)			30.7a	0.27	
						Hairy vetch			25.9ab	0.06	
				NT		No CC			39.8ab		
						Black oat			47.6a	0.34	
						Winter wheat			38.7ab	–0.05	
						Oilseed radish			37.3ab	–0.11	
						Blue lupin			42.9ab	0.13	
						Hairy vetch			33.8b	–0.26	
Washington, USA	na	na	Silt loam, na	Tilled	Corn	No CC	6	0–15	15.2bc		Kuo et al., 1997
						Rye			16.2a	0.17	
						Austrian winter pea (*Pisum sativum* subspecies *arvense* L.)			15.5abc	0.05	
						Ryegrass (*Lolium* sp.)			15.8ab	0.10	
						Hairy vetch			15.4abc	0.03	
						Canola (*Brassica* sp.)			14.6c	–0.10	
					Cover crop had no effect on soil organic C concentration						
Canada	350	3.3	Loam, 18.0 g kg^{-1}	Disk	Spring wheat	No CC	9	0–7.5	17.9		Curtin et al., 2000
						Lentil			18.4	0.06	

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Table 1 (continued).

Location	MAP	MAT	Soil texture, initial SOC	Tillage	Crop	Cover crop	Duration	Depth	SOC conc.	SOC gain	Reference
	mm	°C					yr	cm	g kg^{-1}	g kg^{-1} yr^{-1}	
Prairie Du Sac, WI	787	7.7	Silt loam, na	NT	Corn	No CC, N fertilized	4	0–5	23.46		Jokela et al., 2009
						Kura clover (*Trifolium ambiguum* Bieb.)			24.88	0.36	
						Red clover			24.59	0.28	
						Italian rye (*Lolium multiflorum* Lam.)			24.01	0.13	
						Winter rye			21.51	–0.48	
Ames, IA	834	9.2	Loam to clay loam, na	NT	Corn–soybean	No CC	6	0–5	38.7		Kaspar et al., 2006
						Oat–rye			39.7	0.16	
						Oat			38.9	0.03	
						Rye			39.4	0.12	
Aurora, OR	1063	12.0	Silt loam, na	Tilled	Sweet corn–broccoli (*Brassica oleracea* L.)	No CC	7	0–20	16.4		Mendes et al., 1999
						Red clover			16.3	0.01	
						Triticale			14.6	–0.26	
Mexico	1100	14.0	Loam, 54.5 g kg^{-1}	CT	Corn	No CC	2	0–25	49		Astier et al., 2006
						Oat			49	0	
						Vetch			46	–1.5	
Canada	1167	10.0	Silty clay loam, 16.7 g kg^{-1}	NT	na	No CC	1	0–5	16.92		Hermawan and Bomke, 1997
						Barley			17.47	0.55	
						Rye			17.57	0.65	
						Ryegrass			18.82	1.90	

† No fertilizer applied.

‡ 168 kg N ha^{-1} applied.

§ Average for 4-yr study.

Table 2. Cover crop (CC) effects on rate of soil organic carbon (SOC) stock gain in different locations, climates, soil textural classes, CC species, and duration of CC. MAP = Mean annual precipitation, MAT = mean annual temperature, NT = no-till, CT = conventional till, MB = moldboard plow, na = not available. Means followed by the same lowercase letter within the same study location are not significantly different. Studies are divided into those that documented an increase in SOC and those that documented no change in SOC.

Location	MAP	MAT	Soil texture, initial SOC	Tillage	Crop	Cover crop	Duration	Depth	SOC stocks	SOC gain	Reference
	mm	°C					yr	cm	Mg ha^{-1}	Mg ha^{-1} yr^{-1}	
						Cover crop increased soil organic C stocks					
Hesston, KS	874	14.4	Silt loam, na	NT	Winter wheat–sorghum	No CC	7	0–7.5	13.09b		Blanco-Canqui et al., 2011¶
						Sunn hemp			15.68a	0.37	
						Late maturing soybean			16.99a	0.55	
Italy	900	14.3	Loam, 45.01 g kg^{-1}	Across tillage systems	Durum wheat (*Triticum durum* Desf)–corn–sunflower	No CC	15	0–30	46.6c		Mazzoncini et al., 2011
						Non-legume			48.51bc	0.13	
						Low N legume			50.51ab	0.26	
						High N legume			51.18a	0.31	
South Deerfield, MA	1168	8.8	Sandy loam, 11.62 g kg^{-1}	CT	Corn	No CC†	9	0–25	28.5b		Ding et al., 2006
						Rye†			35.3ab	0.76	
						Hairy vetch–rye†			37.8a	1.03	
						No CC§			32.5b		
						Rye§			39.8a	0.81	
						Hairy vetch–rye§			32.5ab	0	
Pennsylvania, United States	1134	10.8	Silt loam, na	Plowed	Corn–soybean	No CC	15	Plow layer	na	0.29	Drinkwater et al., 1998
						Legume CC			na		
Japan	1154	na	Sandy loam, 80.9 Mg ha^{-1}	Across tillage systems	Rice–soybean	No CC	10	0–30	72.86b		Higashi et al., 2014
						Hairy vetch			80.03ab	0.71	
						Rye			84.70a	1.18	
Illinois	1193	12.9	Silt loam, 23.9 Mg ha^{-1}	NT	Corn–soybean	No CC	8	0–15	25.2a		Olson et al., 2010
						Rye–vetch			24.5a	-0.09	
				Chisel		No CC			17.7b		
						Rye–vetch			20.5a	0.35	
				MB		No CC			17.3a		
						Rye–vetch			17.0a	–0.038	
Illinois	1193	12.9	Silt loam, 23.9 Mg ha^{-1}	NT	Corn–soybean	No CC	12	0–15	26.3b		Olson et al., 2014
						Rye–vetch			31.7a	0.45	
				Chisel		No CC			20.3b		
						Rye–vetch			23.7a	0.28	
				MB		No CC			18.9a		
						Rye–vetch			18.9a	0	
France	1213	12.1	na, na	na	Winter wheat–silage corn	No CC	13	0–90	98.6b		Constantin et al., 2010
						Italian ryegrass			102.9a	0.33	

Continued next page

Table 2 (continued).

Location	MAP	MAT	Soil texture, initial SOC	Tillage	Crop	Cover crop	Duration	Depth	SOC stocks	SOC gain	Reference
	mm	°C					yr	cm	Mg ha^{-1}	Mg ha^{-1} yr^{-1}	
Fort Valley, GA	1258	18.1	Sandy loam, 23.9 Mg ha^{-1}	NT	Tomato (*Solanum lycopersicum* L.) –corn	No CC	6	0– 20	19.9b		Sainju et al., 2002
						Hairy vetch			24.4a	0.75	
				Chisel		No CC			20.1ab		
						Hairy vetch			20.1ab	0.00	
				MB		No CC			20.1b		
						Hairy vetch			20.8b	0.12	
				Across tillage systems	Tomato–eggplant (*Solanum melongena* L.)	No CC	7		14.9b		
						Rye			18.7a	0.54	
						Hairy vetch			18.0a	0.44	
						Crimson clover			17.9a	0.43	
Fort Valley, GA	1258	18.1	Sandy loam, 18.1 Mg ha^{-1}	CT	Tomato–eggplant	No CC	5	0–20	15.4bcd		Sainju et al., 2003
						Rye			17.9a	0.50	
						Hairy vetch			17abc	0.32	
						Crimson clover			17.5ab	0.42	
Fort Valley, GA	1258	18.1	Sandy loam, 11.1 Mg ha^{-1}	NT	Cotton–sorghum	No CC	4	0–10	11ab		Sainju et al., 2005
						Rye			10.6ab	–0.10	
						Hairy vetch			11.2a	0.05	
						Hairy vetch–rye			10.4b	–0.15	
				Chisel		No CC			8.8b		
						Rye			9.3ab	0.13	
						Hairy vetch			9.2ab	0.10	
						Hairy vetch–rye			9.7a	0.23	
				Strip till		No CC			9.5b		
						Rye			10.1ab	0.15	
						Hairy vetch			9.7ab	0.05	
						Hairy vetch–rye			10.3a	0.20	
					Cover crop had no effect on soil organic C stocks						
France	604	11.5	na, na	CT	Winter wheat–barley–pea	No CC	16	0–90	44.7		Constantin et al., 2010
						White mustard			45.7	0.06	
				NT		No CC			44.2		
						White mustard			45.1	0.06	
France	605	10.8	na, na		Sugarbeet (*Beta vulgaris* L.)–winter wheat–pea	No CC	13	0–110	59.7		Constantin et al., 2010
						Winter cereal			61.7	0.15	
East Lansing, MI	785	8.1	Sandy loam, na	NT	Corn–soybean	No CC	3	0–5	9.03		Fronning et al., 2008
						Rye			10.02	0.33	

Continued next page

Table 2 (continued).

Location	MAP	MAT	Soil texture, initial SOC	Tillage	Crop	Cover crop	Duration	Depth	SOC stocks	SOC gain	Reference
	mm	°C					yr	cm	Mg ha^{-1}	Mg ha^{-1} yr^{-1}	
Franklin County, Ohio	1000	11.4	Silty clay loam, na	NT	Corn–soybean	No CC	1	0–10	35.4		Mukherjee and Lal, 2015
						Turnip (*Brassica rapa* L.)–pea			32.5	–2.90	
Urbana, IL	1045	10.9	Silty clay loam, na	Tilled	Soybean	No CC	2	0–50	23.58		Acuña and Villamil, 2014
						Radish			23.99	0.21	
						Radish–buckwheat			23.78	0.10	
						Radish–hairy vetch			24.20	0.31	
						Radish–rye			24.96	0.69	
						Radish–triticale			24.45	0.44	
Fort Valley, GA	1258	18.1	Sandy loam, 10.5 Mg ha^{-1}	NT	Sorghum–cotton	No CC	3	0–10	10.7		Sainju et al., 2006
						Rye			11.2	0.17	
						Hairy vetch			11.5	0.27	
						Hairy vetch–rye			11.0	0.10	
				Chisel		No CC			8.86		
						Rye			9.0	0.05	
						Hairy vetch			9.23	0.12	
						Hairy vetch–rye			9.7	0.28	
				Strip till		No CC			9.57		
						Rye			10.0	0.14	
						Hairy vetch			10.1	0.18	
						Hairy vetch–rye			9.6	0.01	
Fort Valley, GA	1258	18.1	Sandy loam, na	NT	Forage sorghum	No CC	4	0–5	7.81		Sainju et al., 2015
						Rye			7.13	–0.17	
						Hairy vetch			8.12	0.08	
						Hairy vetch–rye			7.78	–0.01	
					Sweet sorghum (*Sorghum vulgare* Pers.)	No CC			7.59		
						Rye			8.84	0.31	
						Hairy vetch			8.95	0.34	
						Hairy vetch–rye			9.24	0.41	

Continued next page

Table 2 (continued).

Location	MAP	MAT	Soil texture, initial SOC	Tillage	Crop	Cover crop	Duration	Depth	SOC stocks	SOC gain	Reference
	mm	°C					yr	cm	Mg ha^{-1}	Mg ha^{-1} yr^{-1}	
Prattville, AL	1437	18.4	Sandy loam, 4.3 g kg^{-1}	NT	Corn–cotton	No CC	6	0–15	14.75		Balkcom et al., 2013¶
						Rye			18.25	0.58	
						Wheat			16	0.21	
				Para till		No CC			15.75		
						Rye			15.25	−0.08	
						Wheat			16	0.04	
				Strip till		No CC			15		
						Rye			17	0.33	
						Wheat			17.5	0.42	
Brazil	1440	19.4	Sandy loam, na	NT	Corn	No CC	10	0–20	19.2		Amado et al., 2006
						Ryegrass			20.8	0.16	
						Velvet bean (*Mucuna pruriens* L.)			25.1	0.59	
Brazil	1769	19.7	Sandy clay loam, na	NT	Corn–oat	No CC	15	0–20	35.6		Amado et al., 2006
						Pigeon pea (*Cajanus cajan* L.)			41.3	0.38	

† No fertilizer applied.

‡ 168 kg N ha^{-1} applied.

§ 202 kg N ha^{-1} applied.

¶ Estimated from published graph.

While there are some tendencies for CC groups to affect SOC concentration differently, the high variability among studies appears to limit differences among CC groups. Among studies reporting significant CC effects on SOC concentration, 5 were under brassicas, 13 under grasses, 17 under legumes, and 3 under mixes (Table 1). Mean annual SOC concentration gains were 0.81 ± 0.75 g kg^{-1} yr^{-1} for brassicas, 0.50 ± 0.38 g kg^{-1} yr^{-1} for grasses, 0.36 ± 0.32 g kg^{-1} yr^{-1} for legumes, and 0.61 ± 0.20 g kg^{-1} yr^{-1} for mixes. These data indicate that CC groups generally do not affect SOC concentration because means and standard deviations were similar among all CC functional groups. Among studies reporting significant CC effects on SOC stocks, 8 used brassicas, 12 used legumes, and 11 used mixes (Table 2). Mean annual stock gains were 0.67 ± 0.29 Mg ha^{-1} yr^{-1} for grasses, 0.43 ± 0.15 Mg ha^{-1} yr^{-1} for legumes, and 0.42 ± 0.28 Mg ha^{-1} yr^{-1} for mixes, indicating no clear differences in trends in SOC stocks among CC species. Our results corroborate those of Poeplau and Don (2015) who compared the rates of SOC stock change between legumes and non-legumes and found no differences. The lack of differences in SOC stocks between mixes and single CC species could be due to biomass yield. Some studies have shown that biomass yield between mixes and single species may not be significantly different (Smith et al., 2014).

Climate data as numerical mean annual temperature and precipitation may show differences in SOC concentration gains under CC. The annual gain rate of SOC concentration ($r = 0.053$; $P > 0.05$; $n = 79$) and annual SOC stock ($r = 0.088$; $P > 0.05$; $n = 71$) with CC was not influenced by mean annual precipitation. Mean annual temperature was not correlated with the annual rate of SOC concentration gain ($r = 0.16$; $P > 0.05$; $n = 79$) or the rate of SOC stock gain under CC ($r = 0.041$; $P > 0.05$; $n = 71$).

Cover crops can also improve soil physical properties, but these properties are generally slow to change with management. Soil aggregate stability may, however, respond more rapidly than other physical properties over relatively short time scales (<3 yr). The use of CC results in positive effects on aggregate stability (Blanco-Canqui et al., 2015). Increased aggregation can increase total porosity and water infiltration rate, and decrease soil compaction parameters (bulk density and penetration resistance). The positive effects on soil aggregation and increase in total porosity can lead to increased water infiltration. Cover crops can increase uptake and cycling of nutrients and reduce nutrient losses to the environment (Blanco-Canqui et al., 2015). Cover crops can increase microbial activity and alter the quantity and diversity of the microbial community because they add substrate diversity and increase quantity of substrates for microbial activity (Jokela et al., 2009; Mbuthia et al., 2015).

USING COVER CROPS TO OFFSET THE NEGATIVE EFFECTS OF RESIDUE REMOVAL ON SOIL CARBON

The Potential of Cover Crops to Offset Effects on Soil Carbon

Based on the above discussion, a potential opportunity exists to manage soil C with CCs (Fig. 4). Gains in SOC under CC can potentially offset the negative impacts of residue removal on SOC (Fig. 5). As indicated earlier, crop residue removal, particularly at high rates (≥50%) reduces SOC concentration and stocks. For example, on an area basis, the average rate of SOC stock loss due to residue removal across different rates of removal was 0.61 Mg ha^{-1} yr^{-1}, whereas CC increase SOC stocks by an average of 0.49 Mg ha^{-1} yr^{-1} (Table 2) in the upper 30 cm of the soil. Therefore, on average, CC appears to have the potential to offset 80% (0.61 vs. 0.49 Mg ha^{-1} yr^{-1}) of the SOC stocks lost due to residue removal. As discussed earlier, SOC stock loss is about 0.31 Mg ha^{-1} yr^{-1} under residue removal rates <50% (Blanco-Canqui and Lal, 2009; Smith et al., 2012), but SOC gains under CC is about 0.49 Mg ha^{-1} yr^{-1} (Table 2).

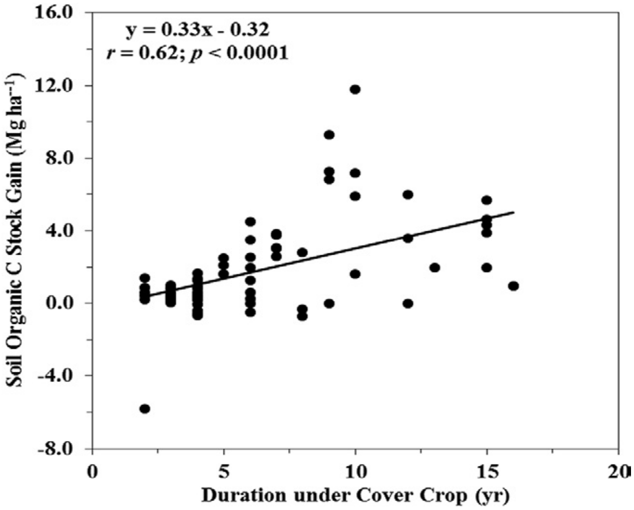

Fig. 3. The correlation between rate of soil organic carbon stock gain and duration under cover crop.

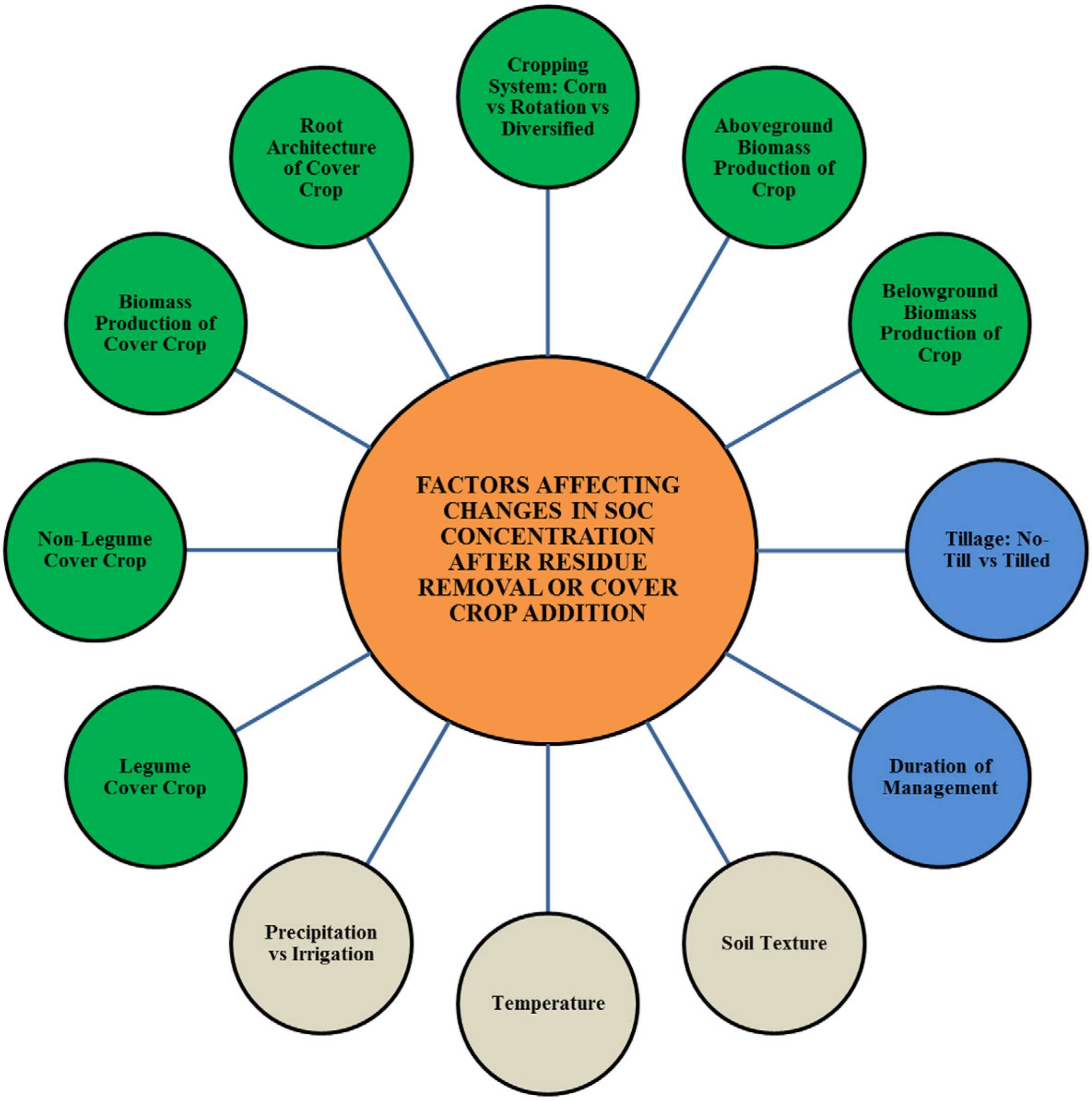

Fig. 2. Factors affecting soil organic carbon (SOC) concentration or stocks after residue removal or cover crop addition. Factor colors indicate general source affecting SOC where green is a plant factor, gray is soil and environmental factor, and blue is management factor.

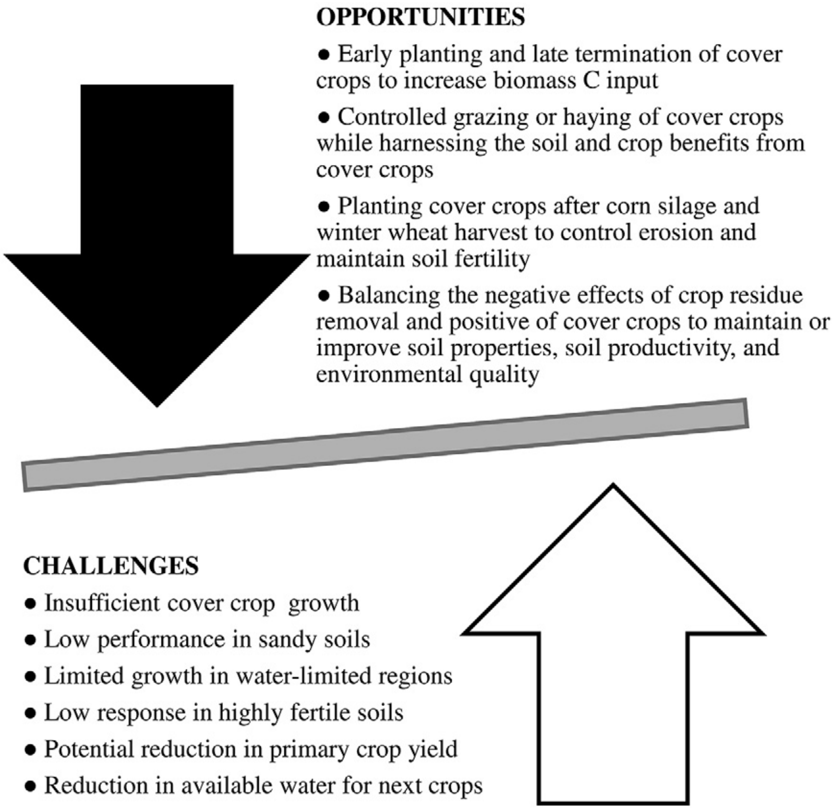

Fig. 4. Opportunities and challenges for integrating cover crop after crop residue removal.

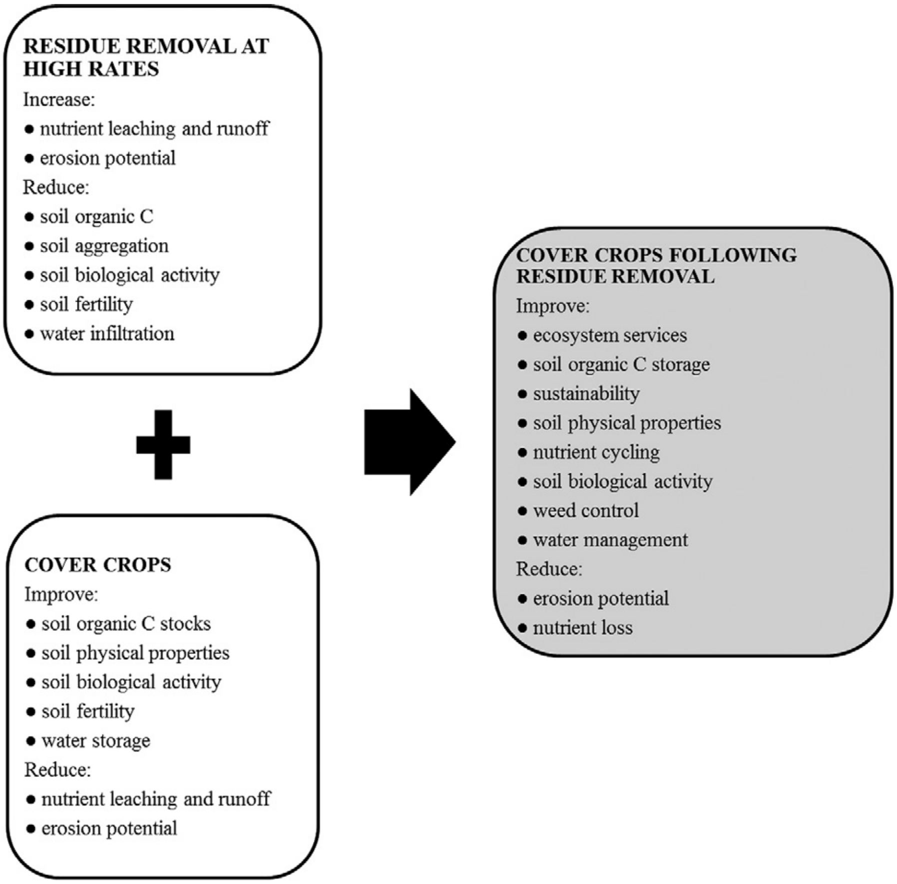

Fig. 5. Examples of the combined effect of cover crop following crop residue removal on soil properties, soil productivity, and environmental quality.

This indicates that CC has the potential to offset 100% of SOC stock lost under low residue removal rates. Similarly, SOC stock loss is 0.87 Mg ha^{-1} yr^{-1} under residue removal rates ≥50% (Blanco-Canqui and Lal, 2009; Smith et al., 2012), indicating that CC could offset approximately 56% of the SOC stock lost under the high residue removal rates. The former scenario is expected as low rates of residue removal remove less C with residues than high rates of removal.

Analysis by tillage systems based on the studies in the reviews by Blanco-Canqui and Lal (2009) and Smith et al. (2012) suggests the following. Under no-till systems, residue removal resulted in SOC stock losses of 1.19 Mg ha^{-1} yr^{-1} on average but CC increased SOC stocks by 0.59 Mg ha^{-1} yr^{-1}, which means CC in no-till systems can potentially offset about 50% of the SOC stocks lost through residue removal. Under plowed systems (moldboard plow, chisel, and others), the reviews above indicated that residue removal reduced SOC stocks by an average of 0.19 Mg ha^{-1} yr^{-1}, but CC increased SOC stocks by an average of 0.53 Mg ha^{-1} yr^{-1}, suggesting CC could offset all of SOC lost with residue removal and tillage. However, there is high variability in the quantity of SOC stocks lost with residue removal and gained with CC under different tillage regimes. Because no-till disturbs the soil the least, we expect CC to offset at least a portion of the SOC stocks or concentration lost with residue removal.

Soil organic C stock losses were often greater than 2 Mg ha^{-1} during the first decade of residue removal, and continued to increase with time (Fig. 6) (Blanco-Canqui and Lal, 2009; Smith et al., 2012). However, CC appeared to result in SOC stock gains that were not >2 Mg ha^{-1} until about 7 yr (Fig. 3). This suggests that CC could offset up to 50% of the SOC lost under residue removal during the first decade, but afterward CC may only offset a fraction of the residue removal induced SOC losses. This suggests that CC following residue-removal may have the greatest impact after the first decade of residue removal.

On a cropping system basis, corn systems lost SOC at a rate of 1.36 Mg ha^{-1} yr^{-1} under residue removal (Blanco-Canqui and Lal, 2009; Smith et al., 2012). Cover crops in similar cropping systems gained SOC stocks at a rate of 0.49 Mg ha^{-1} yr^{-1}, suggesting that CC can offset about 36% of the SOC stocks lost under residue removal in corn or similar systems. Other cropping systems lost SOC stocks at a rate of 0.19 Mg ha^{-1} yr^{-1}, but CC cereal or low biomass systems gained SOC at a rate of 0.49 Mg ha^{-1} yr^{-1}. These data suggest that cereal or low biomass cropping systems, CC could offset all of the SOC stocks or concentration lost.

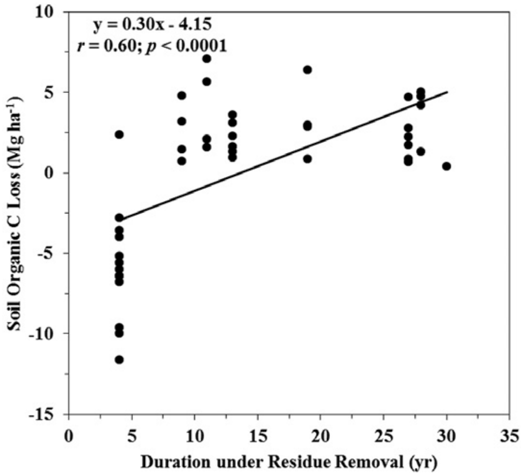

Fig. 6. Change in soil organic carbon (SOC) stock with duration under residue removal (from reviews by Blanco-Canqui and Lal 2009; Smith et al., 2012).

One factor that may affect the quantity of SOC stocks or concentration lost under residue removal, gained under CC and the net SOC balance between both factors is the quantity of biomass input. Different cropping systems produce different quantities of biomass depending on fertilization, climate, soil type, and other factors. For example, corn systems can produce residue quantities ranging from 2 to 12 Mg ha^{-1} (Blanco-Canqui and Lal, 2009; Lou et al., 2011; Schmer et al., 2014). The amount of biomass produced from small grain systems ranged from 1.5 to 7 Mg ha^{-1} (Thomsen and Christensen, 2004; Malhi and Lemke, 2007; Lafond et al., 2009). Cover crop biomass yield may range from 0.56 to 5.03 Mg ha^{-1} for grasses (Kuo et al., 1997; Kaspar et al., 2006; Sainju et al., 2007) and from 3.3 to 9.8 Mg ha^{-1} for legumes (Hubbard et al., 2013). While the range in residue amount produced from cropping systems compared to CC may be similar, there can be differences on a site basis. The differences within a site may lead to imbalances in biomass, leading to reductions in SOC if CC produces less biomass than cropping systems. As an example of how similar CC and residues may be in terms of biomass yield, Balota et al. (2014) reported that biomass yield from CCs to range from 2.98 to 4.34 Mg ha^{-1} and the primary crop residues of corn to range from 3.73 to 4.30 Mg ha^{-1}. In this instance, the removal of residues and use of CC may result in no net loss of SOC.

Studies on Cover Crops following Residue Removal

Based on our linking of the data from reviews on residue removal and CC separately (Tables 1 and 2), CC can have the ability to offset residue removal losses to SOC in some systems. To test this hypothesis, we conducted a review of available published studies that investigated the effects of CC on SOC after residue removal. We found four studies that examined the use of CC and residue removal on SOC stocks (Table 3).

The first study conducted in south central Nebraska for 3 yr found that residue removal at 63% reduced SOC concentration but rye CC had no effect (Blanco-Canqui et al., 2014). One conclusion from this study was that rye CC had limited or no effect on offsetting the SOC lost with corn residue removal in the short term (3 yr). The second study conducted in eastern South Dakota for 4 yr on a silty clay loam found no effect of lentil–wheatgrass CC and corn residue removal (37, 55, and 98%) on SOC stocks in a corn–soybean rotation where lentil CC followed soybean and wheatgrass CC followed corn (Stetson et al., 2012).

The third study was conducted in a silt loam in Pennsylvania, which examined the interactive effects of CC and corn residue removal at rates of 0, 50, and 100% for 5 yr (Adler et al., 2015). The researchers did not observe a change in SOC stocks due to corn residue removal or addition of rye CC (Table 3). The authors suggested that belowground biomass under corn may have been sufficient to balance any SOC loss from the removal of aboveground biomass. The site used in the study by Adler et al. (2015) received dairy cattle manure for 15 yr prior to the study. The addition of manure may have reduced any negative effects of residue removal on SOC stocks. The fourth study was

Table 3. Cover crop (CC) after residue removal effects on rate of soil organic carbon (SOC) concentration or stocks in climates, soil textures, residue removal rates, CC species, and duration of CC under no-till corn rotations to 5-cm depth. MAP = Mean annual precipitation, MAT = Mean annual temperature, na = not available. Means followed by the same lowercase letter within the same study location are not significantly different.

Location	MAP	MAT	Soil texture	Crop	Cover crop	Residue removal rate	Duration	Initial SOC	Final SOC	Reference
	mm	°C				%	yr	—Mg ha^{-1}—		
State College, PA†	1007	10.1	Silt loam	Corn	Rye	0	5	14.5	12.5a	Adler et al., 2015
						50		14.0	13.5a	
						100		13.7	12.5a	
				Corn–soybean		0		14.5	13.0a	
						50		15.0	12.5a	
						100		14.7	12.5a	
Brookings County, South Dakota‡	500	6.1	Silty clay loam	Corn–soybean	No CC	37	4	17.9	17.9a	Stetson et al., 2012
						55			19.3a	
						98			18.2a	
					Lentil–wheatgrass (*Agropyron caninum* L.)					
						37			18.9a	
						55			17.8a	
						98			18.0a	
								—g kg^{-1}—		
Clay Center, NE§	711	10.2	Silt loam	Corn	Across CC	No removal	3	na	40.9a	Blanco-Canqui et al., 2014
					Across CC	63			38.9b	
					No CC	Across removal			38.3a	
					Rye	Across removal			39.9a	
Brookings County, South Dakota‡	500	6.1	Silty clay loam	Soybean	Across CC	37	6	29.1	28.3a	Wegner et al., 2015
						55			27.3a	
						98			25.0b	
				Corn	Across CC	37			31.0a	
						55			30.0a	
						98			26.0b	
				Soybean	No CC	Across residue removal			27.0a	
					Lentil				27.0a	
				Corn	No CC	Across residue removal			29.0a	
					Wheatgrass				29.0a	

† Adler et al. (2015) averaged SOC across CC and did not show CC only, SOC values estimated from the published graph.

‡ Stetson et al. (2012) and Wegner et al. (2015) 37% removal–low, grain only; 55% removal–medium, grain, chop and bale stalks; 98% removal–high, all biomass above 15 cm removed.

§ Blanco-Canqui et al. (2014)–no interaction between residue and CC.

a continuation of the 4-yr study by Stetson et al. (2012) and reported reults after 6 yr (Wegner et al., 2015). Residue removal at 98% reduced SOC concentration but CC had no effect.

The above four studies suggest that CC may not increase SOC concentration in the short term. Cover crops may offset SOC lost with corn residue removal in the longer term (>5 yr), but in the short term, their potential for accumulating SOC appears to be limited. While CC did not significantly increase SOC in the above four studies, CC tended to increase SOC concentration or stocks in two of the four studies (Stetson et al., 2012; Blanco-Canqui et al., 2014). These trends suggest that CC may ameliorate SOC lost from residue removal in the long term. Differences in initial SOC concentration and soil texture may affect the extent to which CC affect SOC gains. Cover crops may not increase SOC concentration in soils with high initial SOC concentration compared to soils with low initial SOC concentration (Stewart et al., 2009). Similarly, soils high in silt and clay content can be more resilient to management changes due to the presence of organo-mineral associations relative to coarse-textured soils. The data from the four studies that incorporated CC after residue removal indicated that CC may not offset residue removal-induced SOC losses. Alternative methods to managing CC may result in CC offsetting residue removal-induced SOC losses.

COVER CROPS TO OFFSET NEGATIVE EFFECTS OF RESIDUE REMOVAL ON OTHER SOIL PROPERTIES

As discussed earlier, CC can in general improve soil properties whereas excessive rates of residue removal can reduce such properties. Thus, addition of CC following residue removal should help offset negative impacts of residue removal. Studies on the effects of CC following residue removal on all properties are, however, few. We discuss the findings from the few available studies next.

Wet Aggregate Stability: An Indicator of Water Erosion Potential

There are no studies on water erosion under CC following crop residue removal, but three studies have measured wet aggregate stability under CC after residue removal. Wet aggregate stability is a key indicator of soil water erosion potential. Larger soil aggregates are less likely to be carried in runoff than small aggregates (microaggregates). The first study conducted in a silty clay loam in eastern South Dakota for 4 yr found that CC did not affect wet aggregate stability, but residue removal at 98% decreased wet aggregate stability by 8% compared to residue removal at 37% (Stetson et al., 2012). Wegner et al. (2015) continued the previous study in South Dakota for an additional 2 yr and found that high rates of residue removal reduced water stable aggregates from 44.2% (98% residue removal) to 37.6% (37% residue removal). Similar to the previous study, CC did not affect wet aggregate stability after 6 yr. These data indicate that CC may not rapidly improve soil's resistance against water erosion after residue removal.

While the percentage of water stable aggregates increases with CC, so does the overall size of water stable aggregates. Blanco-Canqui et al. (2014) found in a 3-yr study in a south central Nebraska silt loam that residue removal of 63% decreased the mean weight diameter of water-stable aggregates (index of aggregate stability) from 1.47 to 1.05 mm, while CC increased the mean weight diameter from 1.03 to 1.49 mm in the same study. This indicated that CC can offset the negative effects of residue removal on wet soil aggregate stability

Together the above studies on wet aggregate stability (Stetson et al., 2012; Blanco-Canqui et al., 2014; Wegner et al., 2015) suggest that CC may or may not offset negative effects of residue removal with regard to wet aggregate stability. Cover crop ability to offset negative effects of residue removal may be dictated by soil texture where fine particles can produce organo-mineral associations and strong macro-aggregates. For example, the lack of CC offsetting residue removal effects on aggregate stability in the study in eastern South Dakota (Stetson et al., 2012; Wegner et al., 2015) may be due to the presence of finer textured soil than in south central Nebraska (Blanco-Canqui et al., 2014). Field data on measured water erosion under CC are needed to evaluate the extent to which CC can reduce water erosion after residue removal. Kaspar et al. (2001) found that CC combined with crop residue can reduce water erosion by up to 93%. This indicated that CC with at least some residue cover can reduce water erosion.

Dry Aggregate Stability: An Indicator of Wind Erosion Potential

Similar to water erosion, there are no studies on actual wind erosion measurements under CC after residue removal. However, there are two studies, which have measured dry aggregate stability under this management regime. This soil property is a sensitive indicator of wind erosion potential. The first study showed that CC tended to decrease the wind erodible fraction from 21 to 14% and tended to increase the size of dry aggregates from 18.9 to 44.4 mm compared to plots without CC on a silt loam in south central Nebraska after 3 yr (Blanco-Canqui et al., 2014). The same study found that residue removal at 63% increased the wind erodible fraction from 4.7 to 30.4% and reduced dry aggregate size from 57.0 to 4.1 mm compared to no residue removal. This study indicated that CC may ameliorate the negative impacts of residue removal on dry aggregate size and thus wind erosion potential.

The second study found that CC decreased the wind erodible fraction when corn residue was removed at high rates in eastern South Dakota (Osborne et al., 2014). In the same study, the wind erodible fraction was similar with and without CC under low residue removal. The results from the above two studies indicate that CC can, in general, reduce the wind erodible fraction and thus offset wind erosion potential after corn residue removal. The potential of CC for offsetting residue removal effects is likely affected by duration of CC use, amount of corn residue produced, and soil texture, among others. For example, the site in eastern South Dakota was rainfed under no-till corn–soybean rotation, whereas the site in a south central Nebraska was irrigated under no-till continuous corn. It is also important to discuss that CC reduced wind erodible fraction in the South Dakota site but not in the Nebraska site. This may be due, in part, to the length of CC management. The CC in the South Dakota site was grown for 6 yr and only for 3 yr in the Nebraska site.

Soil Biology

Cover crops may also increase microbial activity. In eastern South Dakota, Wegner et al. (2015) used the fluorescein diacetate method (FDA) to determine microbial activity in soils from plots with and without residue removal and CC. They found that 98% residue removal decreased microbial activity in soybean by about 10 mg FDA min^{-1} kg^{-1} dry soil compared to low residue removal, but residue removal did not affect microbial activity in corn. Cover crops increased microbial activity in corn after 6 yr from 32.7 to 35.8 mg FDA min^{-1} kg^{-1} dry soil, but CC did not affect microbial activity in soybean.

Particulate organic matter (POM) is a substrate for soil microbial activity and can be affected by CC following residue removal. Osborne et al. (2014) found that CC following residue removal at rates more than 55% decreased POM concentration, but CC only increased POM concentration in low rates of residue removal (37%) in a site in eastern South Dakota (Osborne et al., 2014). In another study in south central Nebraska, CC did not affect coarse or fine POM. However, residue removal reduced fine POM and coarse POM (Blanco-Canqui et al., 2014). The data on POM and soil microbial activity from the above studies suggest that residue removal can rapidly affect POM concentrations, but CC following residue removal may or may not have rapid effects.

OPPORTUNITIES AND CHALLENGES FOR USING COVER CROPS FOLLOWING RESIDUE REMOVAL

Since SOC results from plant biomass, any CC management method that increases CC biomass could result in increased SOC. One method of CC management could be planting CC early, such as after corn silage or wheat or into standing crops just before it reaches maturity. For example, when leguminous CC followed wheat in Kansas, biomass levels were 7 Mg ha^{-1} for sunn hemp and 5.3 Mg ha^{-1} for late maturing soybean (Blanco-Canqui et al., 2011). Cover crop in corn yielded silage systems in Minnesota and Canada had cover crop that was 0.7 to 6.4 Mg ha^{-1} (Krueger et al., 2011; Tollenaar et al., 2011).

Another method of management is terminating CC late, such as a week or within a few days of primary crop planting. Several studies have shown that CC biomass at termination 10 d to 1 mo before planting corn was more than double or triple that of the CC terminated 2 mo before planting corn (Clark et al., 1994; Wagger, 1989; Westgate et al., 2005; Crandall et al., 2005). Presumably, the longer growing period, which resulted in greater CC biomass would result in greater positive effects on soil properties. These studies suggest that early planting and late termination of CC can result in increased CC biomass, which may concomitantly increase SOC levels although experimental data on SOC gains under later termination of CC are not available. Terminating CC late or planting into standing crops has, however, its own challenges. For example, late termination of CC could negatively impact crop yields through plant competition for water and nutrients, especially in semiarid locations, reducing subsequent crop yields.

Use of CC following crop residue removal is not without its challenges (Fig. 5). Cover crop performance and benefits may depend on biomass input, duration, soil texture, initial SOC concentration, and climate. Cover crops must achieve sufficient biomass in a short timeframe to improve soil properties. Cover crop biomass production is highly variable (Clark et al., 1994; Johnson et al., 1998; Kaspar et al., 2001; Krueger et al., 2011; Tollenaar et al., 2011; Nielsen et al., 2015a). For example, CC terminated when small (or early) potentially does not produce sufficient biomass or root systems to increase SOC or improve other properties. However, when CC is grown for longer periods, such as interseeding into the primary crop before maturity, after silage or wheat, or terminating closer to primary crop planting, CC can positively impact soil properties.

Changes in soil properties after CC can be difficult to detect in the short term. Tables 1 and 2 show that 50% of studies using CC for ≤5 yr showed no effect of CC. This suggests that CC can have variable effects on ameliorating any adverse effects of residue removal on soil properties in the short term. Differences in soil texture could also affect CC impacts on soil properties. For example, soils with greater silt or clay content compared to soils with greater sand content may accumulate more SOC as SOC interacts with fine soil particles (Hassink, 1997; Six et al., 2002).

Initial soil C concentration or stock before implementing CC use may impact soil property response to CC. We hypothesized that soils with lower initial SOC concentration could accumulate SOC more rapidly than soils with high initial SOC stocks following CC establishment. The initial SOC stocks for the published studies ranged from 4 to 80 Mg ha^{-1} (Table 2). The rate of annual SOC stock gain with CC was positively correlated with initial SOC stocks (Fig. 7), which suggests that soils with high initial SOC stock could gain more SOC after CC addition. This relationship does not support the hypothesis that soils low in initial SOC can gain SOC concentration at a greater rate. It is important to note, however, that few studies on CC were conducted in soils with low initial SOC. More studies on CC on low organic matter soils are needed to better assess the relationship.

Differences in climate may affect how CC affects soil properties. For example, temperature, as discussed earlier, can impact the amount of SOC gained under CC due to increased biomass production with decreasing temperature (Fig. 4). Regarding precipitation input, it is well known that regions with high precipitation accumulate more SOC compared to those with low

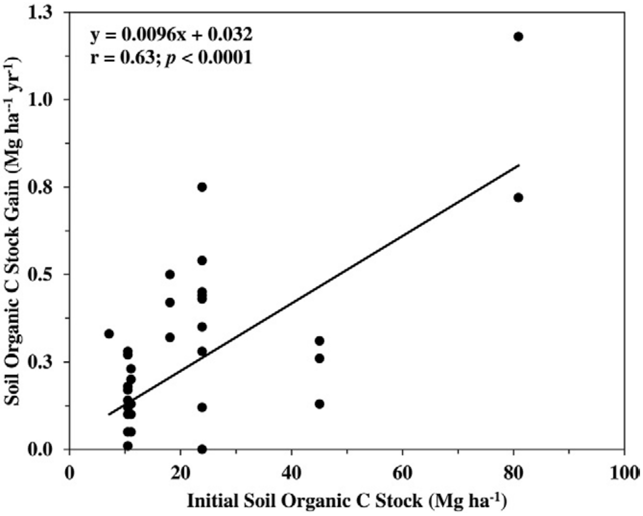

Fig. 7. Correlation between soil organic carbon (SOC) stock gain and initial SOC stock under cover crops.

precipitation due to greater plant biomass production (Trost et al., 2013). However, in this review, mean annual precipitation and the amount of SOC gained under CC were not correlated, suggesting that CC effects on SOC and soil properties do not appear to change with precipitation zone.

Another challenge with CC use, particularly in semiarid locations, is the potential negative impact on primary crop yield (Nielsen and Vigil, 2005; Nielsen et al., 2015b). Fallow periods are used to store soil water for subsequent crops in semiarid regions, but growing CC during this period can use water intended for the primary crop (Nielsen and Vigil, 2005; Nielsen et al., 2015b). An analysis of a few studies from different precipitation zones suggests that CC can decrease primary crop yield as precipitation decreases. For example, a study in Maryland (1034–1202 mm annual precipitation) showed that CC did not negatively impact corn yield (Clark et al., 1994). In a study in Iowa (910 mm annual precipitation), use of CC had mixed effects on corn yield (Johnson et al., 1998). Similarly, in Nebraska (711 mm annual precipitation), CC reduced yield in corn silage in 5 out of 10 yr (Ferguson et al., 2005). In Colorado (421 mm annual precipitation), CC reduced wheat yield during a 6-yr study (Nielsen and Vigil, 2005). The negative effect of CC on yield in Colorado compared with Maryland is most probably due to the 2.6 times (1118 vs. 421 mm) lower precipitation in the semiarid environment.

RESEARCH NEEDS

There are a number of research needs that deserve attention:

1. There is a potential opportunity to combine CC with residue removal to maintain or enhance soil properties and productivity (Fig. 4 and 5). However, research data on this topic are very limited. We found only four studies that evaluated CC effects on SOC and other soil properties after residue removal. Potential of CC for offsetting negative effects of removal most likely depends on site-specific conditions. Therefore, more research on the effect of CC after residue removal on SOC stocks, crop yield, and other soil properties is needed from a wide variety of CC management (i.e., planting and termination dates) scenarios, tillage and cropping systems, soil types with different initial C concentrations, and climatic conditions.

2. Cover crop research on mixtures vs. single CC species is limited. The hypothesis is that mixtures may increase SOC stocks and soil properties more than single species. However, there are few data to support that hypothesis at this point. If mixtures increase SOC and soil properties more than single species, then planting mixtures after crop residue removal may have a greater ability to offset the negative effects of residue removal than single species alone.

3. More CC studies in water-limited or semiarid regions are needed. Use of CC in semiarid regions is not very common, but there is a renewed interest in growing CC in those environments. For example, data from irrigated sites on residue removal, CC, and CC after residue removal are very few. Do irrigated croplands lose more SOC with residue removal compared with rainfed croplands? Does CC offset residue removal effects on SOC more rapidly in irrigated than in rainfed croplands? How might CC and crop residue management need to change with irrigation? Different management strategies and CC species may be required to successfully grow CC in water-limited regions.

4. There is also a need to investigate how CC performance changes with temperature, evapotranspiration, short-growing season, and other growth factors. Precipitation is not the only factor that affects CC growth but rather the combination of all the factors.

5. Data from long-term studies on residue removal, CC, and CC following residue removal are limited. Yet, this information is needed to better to understand how these practices may affect soil properties in the long term. For example, it is important to determine whether or not CC increases SOC stocks indefinitely or whether or not SOC stock reaches effective stabilization capacity (Stewart et al., 2007).

6. Is there a threshold level of residue removal where CC could offset the negative effects of residue removal? If, so what is that level, and in what conditions is it feasible? Understanding this balance and the conditions where the balance occurs warrants more research. Finding the balance between the negative effects of residue removal and the positive effects of CC on soil properties is a priority.

7. Some CC and residue removal studies reported SOC concentration on a mass basis (% or g kg^{-1}) only. This makes comparison of SOC gains or losses on an area basis (Mg ha^{-1}) difficult. Soil bulk density should be included in all measurements for a comprehensive analysis of SOC stocks following CC addition and crop residue removal.

CONCLUSION

Removing crop residues at high rates (≥50%) can reduce SOC concentration and stocks. By contrast, CC can increase SOC concentration and stocks, potentially offsetting residue removal-induced losses to SOC and other soil properties. However, our review found few studies that specifically evaluated CC following residue removal. The few studies indicated that CC following residue removal may or may not offset SOC losses and improve other soil properties in the short term (<6 yr). The limited benefits of CC for increasing SOC could be due to the termination time. Cover crops were commonly terminated early in most previous studies, which did not allow significant biomass accumulation and C input. Some potential opportunities to improve performance of CC after residue removal can include early planting (i.e., interseeding) and late termination of CC. Some challenges that could exist with the combination of CC and residue removal include insufficient CC biomass and reduction in main crop yields in water-limited regions. Additional information on CC effects after residue removal on SOC and other soil properties from a broader range of soil textures, CC mixtures vs. single species, management strategies, and climatic conditions is needed. Overall, CC, in the short term, appears to have limited effects on offsetting residue removal effects on soil properties.

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