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Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils

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Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils

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ABSTRACT

Cover crops (CCs) can provide multiple soil, agricultural production, and environmental benefits. However, a better understanding of such potential ecosystem services is needed. We summarized the current state of knowledge of CC effects on soil C stocks, soil erosion, physical properties, soil water, nutrients, microbial properties, weed control, crop yields, expanded uses, and economics and highlighted research needs. Our review indicates that CCs are multifunctional. Cover crops increase soil organic C stocks (0.1–1 Mg ha^{-1} yr^{-1}) with the magnitude depending on biomass amount, years in CCs, and initial soil C level. Runoff loss can decrease by up to 80% and sediment loss from 40 to 96% with CCs. Wind erosion potential also decreases with CCs, but studies are few. Cover crops alleviate soil compaction, improve soil structural and hydraulic properties, moderate soil temperature, improve microbial properties, recycle nutrients, and suppress weeds. Cover crops increase or have no effect on crop yields but reduce yields in water-limited regions by reducing available water for the subsequent crops. The few available studies indicate that grazing and haying of CCs do not adversely affect soil and crop production, which suggests that CC biomass removal for livestock or biofuel production can be another benefit from CCs. Overall, CCs provide numerous ecosystem services (i.e., soil, crop–livestock systems, and environment), although the magnitude of benefits is highly site specific. More research data are needed on the (i) multi-functionality of CCs for different climates and management scenarios and (ii) short- and long-term economic return from CCs.

Enhancing ecosystem services of current cropping systems is a priority for sustaining crop and livestock production, developing biofuel industries, and maintaining or improving soil and environmental quality. Integrating CCs with existing cropping systems has the potential to enhance ecosystem services such as: (i) food, feed, fiber, and fuel production, (ii) C and other nutrient and water cycling, and (iii) soil, water, and air quality improvement. This is particularly important with increased concerns about the following challenges to agriculture: high production costs, environmental degradation, food security, and climate change. According to the Soil Science Society of America Glossary of Terms, CCs are defined as a "close-growing crop that provides soil protection, seeding protection, and soil improvement between periods of normal crop production, or between trees in orchards and vines in vineyards. When plowed under and incorporated into the soil, CCs may be referred to as green manure crops" (SSSA, 2008).

While the use of CCs is not a new concept, the implications of their re-emerging importance and impacts on ecosystem services such as crop and livestock production and soil and environmental quality deserve further discussion. Historically, CCs have been used to meet a few specific needs (i.e., soil conservation, N_2 fixation, and weed and pest management), but now CC management questions increasingly revolve around the potential multi-functionality of CCs including soil C sequestration, mitigation of greenhouse gas emissions, benefits to "soil health," feed for livestock, biofuel production, farm economics, and others.

There are many studies on CCs assessing soil and crop production, but few have attempted to discuss or integrate all the multiple ecosystem services that CCs provide (Dabney et al., 2001; Snapp et al., 2005). Thus, a summarization of the existing knowledge about potential multiple CC benefits is needed for a broader understanding of CC impacts on soil and agricultural production and identification of knowledge gaps that deserve further research. This summarization will help answer the following question: Can CCs provide multiple ecosystem services to address the current challenges in soil and environmental quality, crop and livestock production, biofuel production, among others?

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Abbreviations: CC, cover crop.

The objectives of this review were to: (i) review and synthesize the current state-of-knowledge of the multiple potential ecosystem services that CCs provide including water and wind erosion control, stabilization and enhancement of soil physical properties, impacts on soil C dynamics, increased soil microbial biomass, expanded uses of CCs (i.e., grazing, biofuel), weed suppression, increased crop yields, and enhanced economics based on published research data from temperate soils, and (ii) highlight CC research needs. The different soil, agricultural production, and environmental parameters as affected by CCs are reviewed and summarized below.

SOIL ECOSYSTEM SERVICES

Soil ecosystem services are defined as conditions and processes through which soils provide benefits to agricultural sustainability and environmental quality (modified from Daily et al., 1997). Soils provide numerous ecosystem services that have both local and global implications, including (i) climate regulation, (ii) provision of food, fiber, and fuel, (iii) regulation of water and air quality, and (iv) agricultural sustainability, among others (Palm et al., 2014). Improving the essential ecosystem services that address food security, environmental quality, and overall agricultural sustainability is important. Cover crops have the potential to contribute to the enhancement of soil properties and processes, which, in turn, affect soil ecosystem services and the multi-functionality of agroecosystems. We recognize that the definition of "ecosystem services" is very broad. Here we review some ecosystem services that CCs provide, including water and wind erosion control, improvement in soil physical properties, soil C sequestration, mitigation of greenhouse gas fluxes, enhancement of soil microbial biomass, forage for livestock production, feedstock for cellulosic ethanol production, weed suppression, yields of subsequent crops, and enhanced economics based on published data. Our overall goal was to examine the extent to which CCs affect such ecosystem services. It is also important to clarify that while we reviewed most ecosystem services provided by CCs, particularly those related to soil ecosystem services, we did not address some categories of ecosystem services in detail, including pest or disease control, social and cultural services, and other broad humankind implications resulting from CC use.

Sequestering Soil Organic Carbon

A mass balance of C (inputs and outputs of C) dictates that CCs should increase soil organic C due to additional above- and belowground biomass C inputs (Blanco-Canqui et al., 2013a). Belowground biomass (roots) inputs can be particularly important to increase the soil organic C concentration. Cover crops influence the pathways of gains and losses of organic C in the soil. For example, because one of the pathways for the loss of organic C is soil erosion, including CCs into cropping systems can reduce soil C losses by reducing soil erosion.

Most studies have found that CCs can increase soil organic C concentrations in the long term. Two studies have recently reviewed CC potential for storing soil organic C. Using data from 37 studies worldwide, Poeplau and Don (2015) estimated that CCs can sequester about 0.32 ± 0.08 Mg ha^{-1} yr^{-1} of C to the 22-cm soil depth. Similarly, Blanco-Canqui et al. (2013a) reported that, in general, inclusion of CCs in no-till systems leads to accumulation of soil organic C of 0.10 to 1 Mg more C per hectare per year compared with no-till systems without CCs. Recently, in Illinois, Olson et al. (2014) found that hairy vetch (*Vicia villosa* Roth) and cereal rye (*Secale cereale* L.) CCs sequestered 0.88 Mg ha^{-1} yr^{-1} under no-till, 0.49 Mg ha^{-1} yr^{-1} under chisel plow, and only 0.1 Mg ha^{-1} yr^{-1} under moldboard plow for the 0- to 75-cm depth after 12 yr of management.

The extent to which CCs increase soil C is site specific and depends on: (i) CC biomass input, (ii) years in CCs, (iii) antecedent soil C level, (iv) soil type, (v) CC species, (vi) tillage management, and (vii) climate, among others, as follows:

1. While, in the long term, CCs generally increase the soil organic C concentration, their effects are not detectable in the first few years after establishment (Acuna and Villamil, 2014; Blanco-Canqui et al., 2014). High spatial field variability or soil heterogeneity and insufficient sampling contribute to the difficulty in detecting short-term changes in soil organic C concentration under CCs.
2. Soil C accumulation with CCs varies with soil textural class. For example, the ability of the soil to store and protect soil organic C is positively correlated with the clay content of the soil (Hassink and Whitmore, 1997). Also, eroded soils with low initial C levels can have a greater capacity to accumulate C with CCs (Berhe et al., 2007).
3. Both quantity and quality affect soil C accumulation. Grass CCs are more effective at increasing soil C levels than legume CCs due to slower decomposition of grass CC residues (Blanco-Canqui et al., 2013a). Similarly, mixtures of different CC species can increase soil organic C more than a single-species cover due to the greater above- and belowground biomass production (Fae et al., 2009). In Ohio, Stavi et al. (2012) found that a mixture of Austrian winter pea (*Pisum sativum* L.) and radish (*Raphanus sativus* L.) had greater (19.4 g kg^{-1}) soil organic C concentration than winter pea (15.9 g kg^{-1}) or radish (17.6 g kg^{-1}) alone.
4. Cover crop benefits are detectable more rapidly under no-till management due to reduced residue decomposition rates compared with conventional tillage. Olson et al. (2014) reported that CCs managed under different tillage systems increased soil organic C concentration in the order: no-till > chisel plow > moldboard plow.
5. Precipitation amount affects CC biomass production and C inputs. For example, in semiarid areas, soil organic C can increase with CCs, but because of lower biomass production due to low rainfall, it takes longer to accumulate than in regions with high precipitation (>500 mm). In Garden City, KS, a region with a mean annual precipitation of 489 mm, winter and spring triticale (×*Triticosecale* Wittm.) increased the soil organic C pool by 0.56 Mg ha^{-1} yr^{-1} while spring lentil (*Lens culinaris* Medikus) increased the soil organic C pool by 0.44 Mg ha^{-1} yr^{-1} in the 0- to 7.5-cm depth relative to fallow after 5 yr of management when CCs were grown during the fallow period in winter wheat (*Triticum aestivum* L.)–fallow systems (Blanco-Canqui et al., 2013a). Nine months after termination, however, the CCs had no effect on soil organic C, suggesting that CC benefits are short lived in semiarid climates.

It is well recognized that no-till management often increases the soil organic C concentration near the surface compared with conventionally tilled systems (Blanco-Canqui et al., 2011). However, the addition of CCs to existing no-till cropping systems can further increase soil organic C storage compared with no-till alone (Fig. 1). The use of deep-rooted CCs can favor soil organic C accumulation in deeper no-till soil depths (Stavi et al., 2012). The potential of CCs to accumulate soil C at deeper depths in the soil profile warrants further research under different CC species.

Reducing Soil Erosion

Water Erosion

While the benefits of CCs for reducing water erosion are widely recognized, actual runoff and sediment loss data are rather few (Table 1; Kaspar et al., 2001; Krutz et al., 2009). Runoff loss can decrease by up to 80% and sediment loss from 40 to 96% with CCs (Table 1; Kaspar et al., 2001). The magnitude by which CCs reduce water erosion is a function of biomass production and CC species. In a 3-yr study in Iowa, Kaspar et al. (2001) observed that rye reduced runoff by 10% in 1 of the 3 yr, but oat (*Avena sativa* L.) did not reduce runoff. Across the 3 yr, rye and oat reduced rill erosion by 54 and 89%, respectively, but interrill erosion was reduced in 2 of the 3 yr by rye and in only 1 of the 3 yr by oat. In western Kansas, winter triticale reduced water erosion more than winter lentil or spring pea (Table 1), attributed to the greater biomass production of winter triticale.

Cover crops also reduce the loss of dissolved nutrients in runoff, particularly total P and NO_3–N, which can result in improved water quality, soil fertility, and crop productivity (Kaspar et al., 2001). For example, in Missouri, winter CCs reduced dissolved nutrient losses by 7 to 77% (Zhu et al., 1989). Likewise, in New York, Kleinman et al. (2005) reported that total P loads in runoff were 74% lower in plots with CCs than in plots without CCs. The reduction in water erosion suggests that CCs improve water quality and reduce pollution of the streams, rivers, lakes, and other water sources.

Cover crops reduce losses of sediment and nutrients in runoff by (i) providing protective cover to the soil, (ii) absorbing raindrop energy, (iii) reducing soil aggregate detachment, (iv) increasing soil surface roughness, (v) delaying runoff initiation, (vi) intercepting runoff, (vii) reducing runoff velocity, (viii) increasing the opportunity time for water infiltration, and (ix) promoting the formation of water-stable aggregates (Blanco-Canqui et al., 2011).

The effectiveness of CCs depends on the CC species due to differences in biomass cover. Planting a mix of different CC species (i.e., grasses and legumes) can provide more canopy cover, more total biomass yield, and more uniform surface cover than a single species alone (Wortman et al., 2012b), resulting in greater water erosion control. Information on the use of a wide range of CC species or mixtures for controlling water erosion is not available. Similarly, most water erosion studies are from regions with high annual precipitation (>500 mm) and little information exists for soils in semiarid regions (<500 mm) such as the central Great Plains (Table 1). If successfully established and managed in semiarid regions, CCs not only reduce water erosion (Table 1; Blanco-Canqui et al., 2013a) but also capture rain or irrigation water.

Wind Erosion

Reduced wind erosion is another ecosystem service of CCs (Bilbro, 1991; Unger and Vigil, 1998). Wind erosion is a major environmental concern in semiarid soils such as those in the Great Plains. Soil losses due to wind erosion in this region range from 5 to 18 Mg ha^{-1} yr^{-1} (Hansen et al., 2012). Soils are susceptible to wind erosion in late winter and early spring when primary crops are absent and winds are high. If winter and spring CCs are successfully grown during this period in

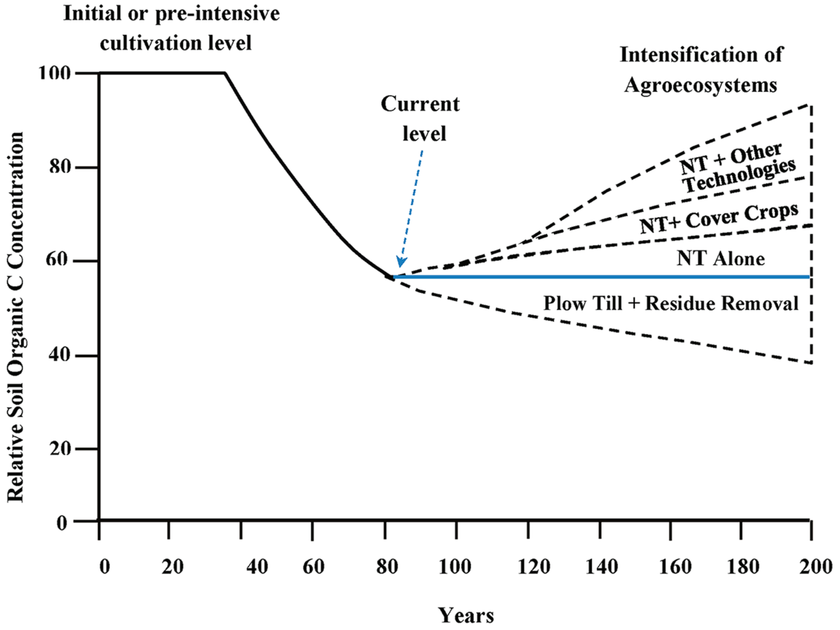


Fig. 1. Intensive tillage has reduced soil organic C levels relative to pre-cultivation levels. No-till (NT) technology can maintain or increase soil C levels. Inclusion of cover crops in no-till systems can be additional technology to enhance the potential of no-till systems to increase soil organic C concentration through the input of additional aboveground and belowground biomass (Blanco-Canqui et al., 2011; Olson et al., 2014) (graph not to scale).

Table 1. Data on cover crop (CC) effects on runoff and soil loss from select studies. Studies that did not report soil loss in megagrams per hectare were not included.

Study site	Precipitation	Soil and slope	Tillage	Crop	Cover crop treatments	Runoff	Soil loss	Runoff reduction	Soil loss reduction	Reference
	mm yr^{-1}					mm	Mg ha^{-1}	%	%	
Kingdom City, MI	996	silt loam, 3–3.5%	no-till	corn	no CC	245a†‡	22a‡			Wendt and Burwell (1985)
					rye	122b	0.9b	50	96	
Kingdom City, MI	996	silt loam, 3%	no-till	soybean	no CC	179a‡	1.517a‡			Zhu et al. (1989)
					chickweed (*Stelidria media* L.)	100b	0.197b	44	87	
					Canada bluegrass (*Poa compressa* L.)	99b	0.062b	45	95	
					downy brome (*Bromus teetorum* L.)	85b	0.078b	53	96	
Reidsville, NC	1129	sandy loam, 4%	moldboard plow	corn	no CC	23.6a‡	41.3‡			Martin and Cassel (1992)
					rye and hairy vetch	20.4a	3.3	13	92	
Garden City, KS	462§	silt loam, 1–3%	no-till	wheat	no CC	45a	1.59a			Blanco-Canqui et al. (2013a)
					winter lentil	26ab	0.97ab	42	39	
					spring triticale	17b	0.61ab	62	61	
					spring pea	12b	0.51b	73	68	
					winter triticale	10b	0.34b	78	79	

† Means followed by different lowercase letters in a column within the same study are different at $P < 0.05$.

‡ Data averaged across study years.

§ This study was conducted under simulated rainfall at 63.5 mm h^{-1}.

semiarid environments, they can be useful for reducing the risk of wind erosion (Blanco-Canqui et al., 2013a).

Adding CCs to cropping systems with limited annual residue input can reduce wind erosion. In northwestern Texas, Bilbro (1991) found that a winter rye CC planted with forage sorghum [*Sorghum bicolor* (L.) Moench] reduced the wind erosion potential on a fine sandy loam soil. Also, growing CCs during the fallow period (about 14 mo) of crop–fallow systems can reduce wind erosion. In a semiarid silt loam in southwestern Kansas, CCs planted during fallow in a wheat–fallow rotation reduced the soil's susceptibility to wind erosion by reducing the amount of wind-erodible fraction (<0.84-mm diameter) by 80% and increasing the dry aggregate size by 60%, although the effectiveness of the CCs varied by plant species, termination time, and time after CC termination (Blanco-Canqui et al., 2013a; Fig. 2). The same study revealed that winter and spring triticale CC species were more effective at reducing soil erodibility due to their higher biomass production compared with CCs with limited biomass production (i.e., lentil, spring pea). Grasses are more effective than legume CCs for reducing wind erosion, mainly due to the greater height of standing residues and slower decomposition of residues.

Cover crops reduce wind erosion risks by physically protecting the soil surface, improving soil structural properties, increasing the soil organic C concentration, and anchoring the soil with their roots when primary crops are not in place, thereby reducing potential soil erodibility. An increase in soil organic C with CCs is one of the main factors contributing to increased aggregate stability and reduced wind-erodible fraction because organic C can physically, chemically, and biologically bind soil particles and form stable macroaggregates (Colazo and Buschiazzo, 2010).

Reduced wind erosion by CCs has many beneficial impacts to society. In addition to conserving the soil, it can improve air quality. Particulate or dust emissions from agricultural lands can be transported long distances, posing a threat to human and animal health (i.e., shortness of breath, respiratory disorders; USDA–ARS, 2000). The Dust Bowl is a reminder of the consequences of severe wind erosion on agriculture and society. The inclusion of CCs in current cropping systems offers promise to manage dust emissions from agricultural lands, thereby reducing air pollution (Bilbro, 1991; Blanco-Canqui et al., 2013a).

Improving the Soil Physical Environment

Soil Compaction

Soil compaction is increasingly becoming a concern as farm equipment, including tractors, combines, and grain carts, become larger and heavier. For example, tractor weights have increased from 4 Mg in the 1940s to 20 to 45 Mg in the 2000s (Sidhu and Duiker, 2006). Moreover, producers sometimes have to get into fields when the soil is wet and susceptible to compaction to achieve timely crop harvest, planting, fertilization, weed control, and other field operations. It is well documented that compaction reduces water, heat, and gas flow, nutrient and water uptake, root growth, and crop yields (Schafer-Landefeld et al., 2004).

Cover crops can (i) alleviate soil compaction and (ii) reduce the susceptibility of the soil to compaction. The extent of this benefit will depend on the CC species, the

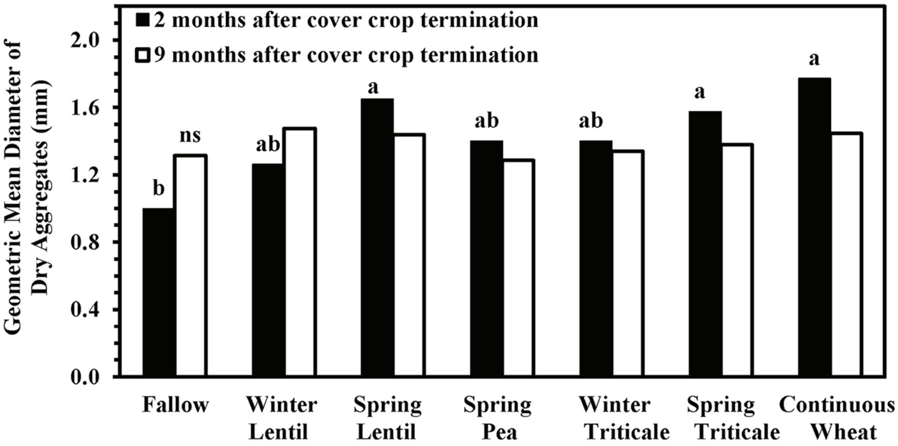


Fig. 2. Effects of winter and spring cover on soil dry aggregate stability with time after termination when cover crops were planted during the fallow period in the fifth year of a wheat–fallow system in a semiarid soil in southwestern Kansas (Blanco-Canqui et al., 2013a). Means with different lowercase letters within the same sampling time are significantly different at $P < 0.05$; ns = not significant.

length of CC growth, and the amount and characteristics of the belowground biomass input (i.e., the length and size of roots; Chen and Weil, 2010). Cover crops with deep taproots such as brassicas (radish) can alleviate soil compaction by penetrating compact layers and acting like tillage tools or bio-drills. Across different soils (silt loam, sandy loam, and loamy sand) in Maryland, Chen and Weil (2010) reported that the number of roots that penetrated compacted layers under no-till soils in the 0- to 50-cm depth by species were in the order: forage radish > rapeseed (*Brassica napus* L.) > rye. Taproots have more biological drilling potential than fibrous roots because the latter are often concentrated near the soil surface (Cresswell and Kirkegaard, 1995). After CC termination, taproots also create large bio-channels or macropores to increase water and air flow along with root proliferation of the main crop to deeper layers (Chen and Weil, 2010).

Cover crops can reduce compactibility (susceptibility of the soil to compaction) by improving soil aggregation and increasing the soil organic C concentration. For example, the accumulation of soil organic C with time under CCs reduces near-surface soil compactibility (Blanco-Canqui et al., 2012). Soil compactibility is measured by the Proctor test at different soil water contents under the same compaction pressure (Blanco-Canqui et al., 2012). On a silt loam in eastern Kansas, the addition of summer CCs including sunn hemp (*Crotalaria juncea* L.) and late-maturing soybean [*Glycine max* (L.) Merr.] to a no-till winter wheat–grain sorghum system reduced near-surface soil compactibility by 5% after 15 yr of management. Maximum bulk density under summer CCs was lower in the 0- to 7.5-cm depth than under plots without CCs (Fig. 3A; Blanco-Canqui et al., 2012).

The same study found that the soil critical water content at which maximum compaction occurs was greater under CCs, which suggests that soils under CCs can be trafficked at greater soil water content without causing soil compaction compared with soils without CCs. In that study, the decrease in Proctor bulk density and increase in critical water content were correlated with the soil organic C concentration, indicating that soil compactibility decreases as the soil organic C concentration increases the near-surface layers (Fig. 3B). Soil organic C has

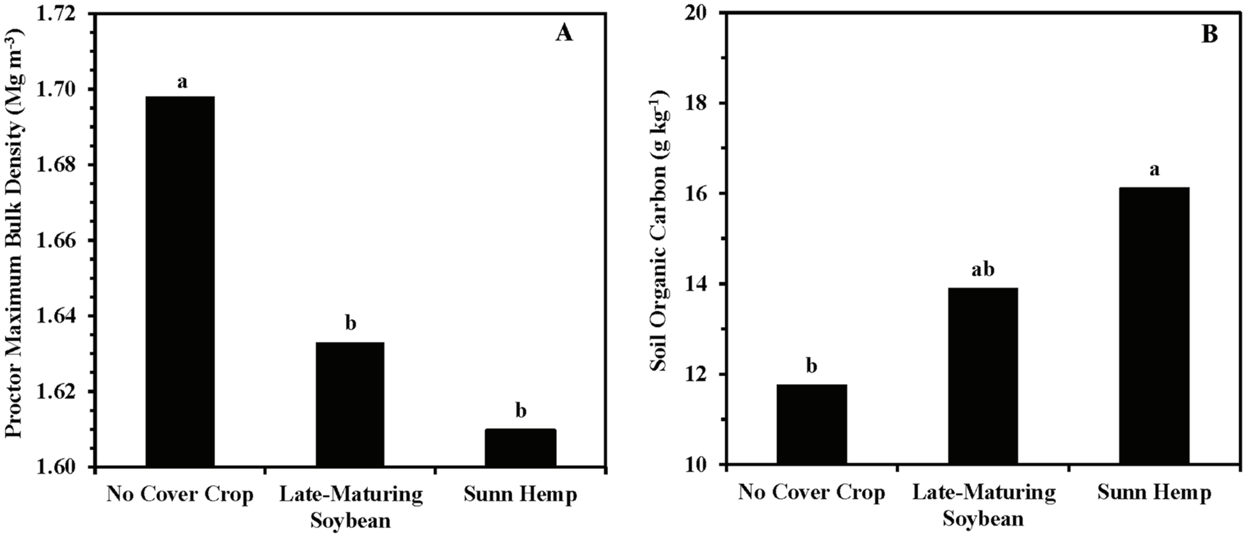


Fig. 3. Response of (A) Proctor maximum bulk density (maximum soil compactibility) and (B) soil organic C at the 0- to 7.5-cm depth to the addition of summer cover crops to a no-till winter wheat–grain sorghum rotation with 0 kg N ha^{-1} applied after 15 yr in south-central Kansas (adapted from Blanco-Canqui et al., 2012).

low density and can thus dilute the bulk density of the whole soil, reducing soil compaction risks. The significant correlation between soil organic C and compactibility suggests that CCs do not reduce soil compactibility until the soil organic C concentration increases in the long term.

Table 2 summarizes six studies on CCs and their effects on bulk density. Cover crops reduced bulk density in four studies and had no effect in two, which suggests that CCs do not always reduce bulk density. Changes in bulk density can be a function of CC management length. Two of the studies reporting lower bulk density were 15-yr (Blanco-Canqui et al., 2011) and 13-yr (Steele et al., 2012) CC experiments, suggesting that CCs reduce bulk density in the long term (Table 2).

Penetration resistance is another measure of soil compaction or strength. The few studies available showed that CCs reduce penetration resistance. Folorunso et al. (1992) reported that CCs reduced near-surface (<1-cm depth) penetration resistance values by about 65% at two sites in California. Abdollahi and Munkholm (2014) reported that Brassicaceae CCs reduced penetration resistance at the 32- to 38-cm depth in tilled soils in Denmark after 10 yr and concluded that CCs can reduce compaction risks in the plow pan region across tillage treatments.

Soil Structural and Hydraulic Properties

Cover crops can positively affect soil physical properties, particularly in the long term, although data are relatively few. One of the soil physical properties that has been frequently measured under CCs is wet soil aggregate stability. Seven out of 11 studies found that CCs increased wet aggregate stability, while four found no effects (Table 2). These results indicate that CCs generally improve soil aggregation. Soil aggregates under CCs are larger and more stable than those without CCs. Water-stable aggregates under CCs are 1.2 to 2 times larger than under soils without CCs (Table 2). Even under conventional tillage, CCs increase soil aggregate stability (McVay et al., 1989; Liu et al., 2005). Note that most studies have been conducted in regions with >500 mm of annual precipitation (Table 2).

Cover crops appear to rapidly improve soil aggregation (<3 yr; Table 2). This suggests that soil aggregate stability is one of the most responsive parameters to CC management. The rapid improvement in soil aggregate stability under CCs can enhance water, nutrient, and C storage, soil macroporosity, and root growth while reducing soil erodibility (Blanco-Canqui et al., 2013b). Cover crops increase aggregate stability by protecting the soil surface from raindrop impact, providing additional biomass input (i.e., roots), and increasing soil organic C concentration and microbial activity (Fig. 4). An increase in soil organic C concentration is positively correlated with an increase in soil aggregate stability (Blanco-Canqui et al., 2013b). Cover crop residues can generate transient, temporary, and permanent organic binding agents to promote soil aggregation (Tisdall and Oades, 1982).

Cover crops can also improve soil hydraulic properties (i.e., water infiltration, water retention capacity, and saturated hydraulic conductivity) through increased soil aggregation. While studies are few, the increase in water infiltration has ranged from 1.1 to 2.7 times (Table 3). Effects on other hydraulic properties are not often measurable in the first 5 yr. In North Carolina, hairy vetch (*Vicia villosa* Roth) and winter wheat in no-till corn (*Zea mays* L.) had no effect on the saturated hydraulic conductivity of a sandy loam after 3 yr of management (Wagger and Denton, 1989). However, in the long term, CCs can result in improved soil hydraulic properties. After 17 yr of management on silt loam and loam soils in Arkansas, winter rye, hairy vetch, and crimson clover (*Trifolium incarnatum* L.) increased soil porosity, saturated hydraulic conductivity, and water retention capacity (Keisling et al., 1994). Cover crops increase: (i) water infiltration by protecting the soil surface and improving soil surface properties and (ii) hydraulic conductivity by increasing macroporosity and pore connectivity. The increased water infiltration under CCs can increase precipitation capture and water storage.

Cover crops combined with no-till management can improve soil physical properties more than CCs with conventional tillage systems. Tillage disrupts soil aggregation and accelerates soil organic C mineralization and can reduce the soil benefits of CCs relative to no-till or reduced tillage management (Sainju et al., 2003). The benefits of CCs can also vary with soil textural class. McVay et al. (1989) reported that crimson clover and hairy vetch increased wet aggregate stability on a sandy clay loam but not on a clay loam after 3 yr. There is limited literature documentation of the effects of CCs on soil physical and hydraulic properties, highlighting the need for more comprehensive characterization of these properties under different soil textural classes.

Soil Temperature

Cover crops moderate soil temperature and reduce abrupt fluctuations in temperature by intercepting incoming solar radiation and insulating the soil. Cover crops reduce the amplitude of day and night soil temperature fluctuations by reducing the maximum soil temperature and increasing the minimum soil temperature. The amount of CC canopy cover or residue input determines the magnitude to which CCs affect soil temperature (Dabney et al., 2001).

Cover crops can reduce the maximum soil temperature by as much as 5°C and increase the minimum soil temperature by about 1°C in temperate regions (Teasdale and Mohler, 1993; Blanco-Canqui et al., 2011). Kahimba et al. (2008) reported that soil in the upper profile under berseem clover (*Trifolium alexandrium* L.) CCs was about 3°C warmer in fall and about 4°C cooler in spring in the eastern Canadian prairies. Similarly, in south-central Kansas, the early spring soil temperature under no-till winter wheat–grain sorghum plots with sunn hemp and late-maturing soybean as summer CCs planted following wheat was 4, 3, and 2°C lower than under plots without CCs at the 4-, 10-, and 20-cm depths, respectively (Blanco-Canqui et al., 2011). The decrease in daytime soil temperature and increase in nighttime soil temperature under CCs are larger near the soil surface than at greater depths (Blanco-Canqui et al., 2011). Soils under CC residues can be warmer in winter and cooler in spring and summer (Kahimba et al., 2008). The lower soil temperature in summer can reduce evaporation and contribute to increased soil water storage. The slow warming in spring can be beneficial in warm climates, but in cool climates, CC residues can delay soil warming, reduce

Table 2. Cover crop (CC) effects on soil bulk density and wet aggregate stability across different precipitation zones, soil types, tillage systems, and cover crop species. Means followed by different lowercase letters in a column within the same study or location are different at $P < 0.05$.

Study site	Precipitation	Soil texture	Tillage	Crop	Cover crop planting time	Time after experiment start	Depth of soil sampling	Cover crop treatments	Bulk density	Water-stable aggregates	Mean weight diameter	Reference
	mm yr^{-1}					yr	cm		Mg m^{-3}	%	mm	
Limestone valley, Georgia	1580	clay loam	no-till	corn	winter	3	0–2.5	no CC		56.3ns†		McVay et al. (1989)
								crimson clover		55.0		
								hairy vetch		58.2		
								wheat		65.1		
Coastal plain, Georgia	1256	sandy clay loam	conventional tillage	grain sorghum	winter	3	0–2.5	no CC		28.9b‡		McVay et al. (1989)
								crimson clover		37.9a		
								hairy vetch		36.7a		
								wheat		32.6ab		
Tifton, GA	1192	loamy sand	no-till	sweet corn	fall + winter	3	0–7.6	no CC	1.73a			Hubbard et al. (2013)
								sunn hemp	1.71b			
Rocky Mount, NC	1190	fine sandy loam	no-till	corn	winter	3	2.5–10	no CC	1.44ns			Wagger and Denton (1989)
								Wheat	1.52			
								hairy vetch	1.47			
Urbana, IL	1050	silt loam	no-till	corn–soybean	winter	5	0–5 (bulk density), 0–15 (wet aggregate stability)	no CC	1.32a	38b		Villamil et al. (2006)
								rye	1.24b	41a		
								hairy vetch	1.23b	43a		
								rye + hairy vetch	1.23b	44a		
Urbana, IL	1050	silty clay loam	conventional tillage	soybean	fall	1	0–50	no CC		82.6ns		Acuna and Villamil (2014)
								CCs		84.2		
Fraser River delta, British Columbia, Canada	1167	silty clay loam	disked	annuals	winter	1	0–5	no CC			1.25b	Hermawan and Bomke (1997)
								barley (*Hordeum vulgare* L.)			1.3b	
								fall rye			1.7a	
								ryegrass			2.0a	
Fort Valley, GA	1160	sandy loam	conventional tillage	tomato–eggplant (*Solanum melongena* l.)	winter	5	0–20	no CC			1.70ns	Sainju et al. (2003)
								rye			1.75	
								hairy vetch			1.71	
								crimson clover			1.66	
Vancouver, BC	1160	silty clay loam	conventional tillage	potato	fall	.67	0–20	no CC			1.24c	Liu et al. (2005)
								annual ryegrass			1.99a	
								fall rye			1.67ab	
								spring barley			1.35bc	
Urbana, IL	1050	silt loam	no-till	corn–soybean	winter	5	0–5 (bulk density) 0–15 (wet aggregate stability)	no CC	1.32a		38b	Villamil et al. (2006)
								rye	1.24b		41a	
								hairy vetch	1.23b		43a	
								rye + hairy vetch	1.23b		44a	
Urbana, IL	1050	silty clay loam	conventional tillage	soybean	fall	1	0–50	no CC			82.6ns	Acuna and Villamil (2014)
								CCs			84.2	
Coastal plain, Maryland	1033	silt loam	no-till	corn	winter	13	0–7	no CC	1.4a		0.42b	Steele et al. (2012)
								rye	1.30b		0.56a	
Hesston, KS	830	silt loam	no-till	wheat–grain sorghum	summer CCs	15	0–7.5	no CC	1.27a		0.42b	Blanco-Canqui et al. (2011)
								late-maturing soybean	1.24ab		0.76a	
								Sunn hemp	1.23b		0.76a	

† ns, not significant at $p < 0.05$.

‡ Lowercase letters in a column within the same study site indicate significant differences at $p < 0.05$.

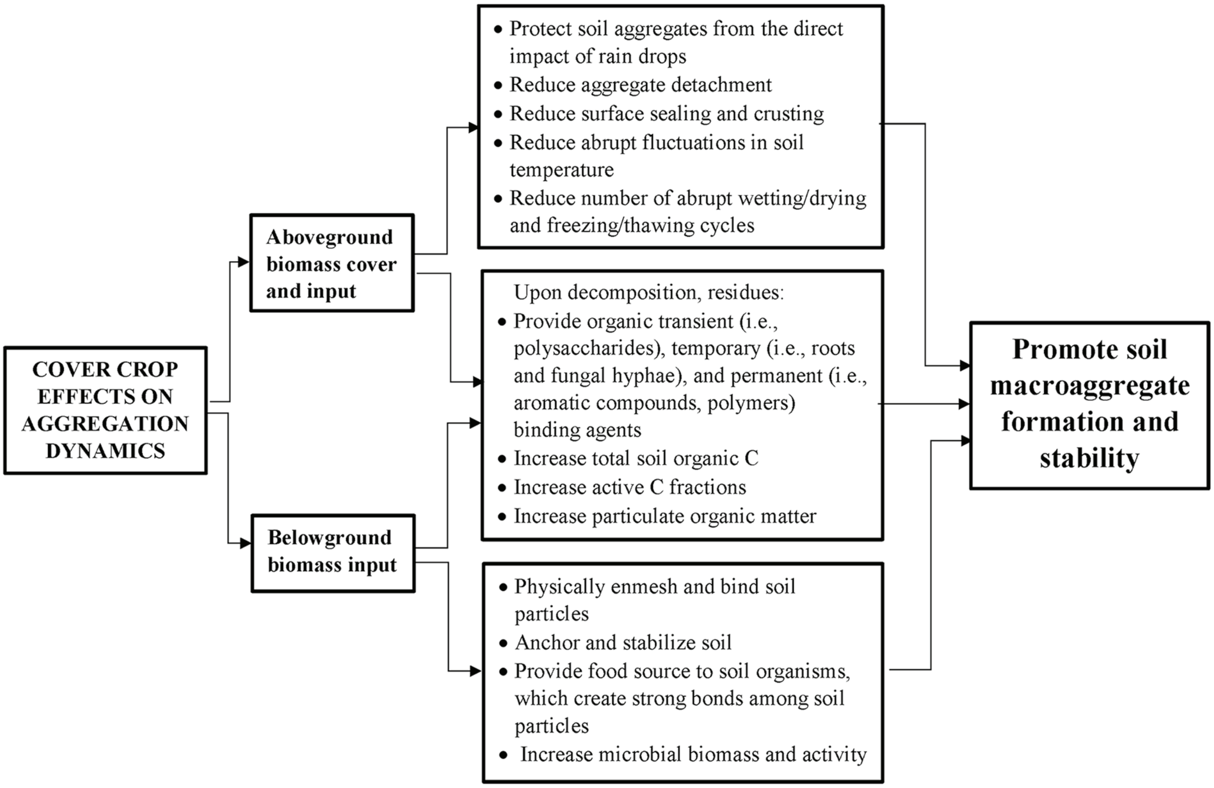


Fig. 4. Mechanisms by which cover crops influence soil physical, chemical, and biological processes contributing to the formation of stable macroaggregates.

seed germination, and adversely affect crop establishment, particularly in no-till soils.

Cover crop residue effects on soil temperature can vary among seasons, tillage systems, CC species, and surface residue cover (Teasdale, 1993). First, CC residues will have greater benefits on moderating soil temperatures when left on the soil surface, such as under no-till management, than when plowed under or incorporated into the soil. Second, the effectiveness of CC residues can diminish with time as residues decompose. Decomposition of crop residues with time often follows an exponential function and depends on residue quality, microbial activity, tillage management, and climate. Third, under an equivalent amount of biomass input, the effectiveness of CC residues at moderating soil temperature varies among CC species due to differences in C/N ratios and residue decomposition rates. Legume CCs tend to decompose more rapidly than non-legume CCs, which can reduce legume CC residue effectiveness at protecting the soil surface and moderating soil temperatures compared with grass CCs. Teasdale (1993) reported that a rye CC was slightly more effective at reducing the maximum soil temperature than hairy vetch due to the slower decomposition of rye residues, and rye relative effectiveness increased as residue decomposition increased with time. While soil temperature effects of CCs can vary with plant species, in general, the total CC biomass input will have a greater impact on soil temperature than the CC species.

Cover crops can also alter freeze–thaw cycles, reduce the depth to which the soil is frozen in winter, and thus contribute to early soil thawing in spring. In the eastern Canadian prairies, Kahimba et al. (2008) reported that no-till plots without CCs had soil profiles frozen to a depth of 0.4 m, but those with CCs had frozen soil only to a depth of 0.2 m in late fall. They also found that, in spring, the frozen soil layer extended to a 0.6-m depth in plots without CCs, but it only extended to a 0.4-m depth in plots with CCs, indicating that CCs not only delay soil freezing but also reduce the depth of frozen soil, which can favor early soil thawing. In turn, early thawing can increase water infiltration, improve soil drainage, increase N mineralization, and allow early planting of subsequent crops in cool climates.

Cover crops moderate the soil temperature by increasing the minimum soil temperature and decreasing the maximum soil temperature. Cover crops can reduce soil temperatures in summer, which reduces evaporation and conserves water. By regulating the soil temperature or reducing temperature extremes, CCs can also favor other soil processes such as aggregation, microbial activity, residue decomposition rates, and water storage, but more research is needed to document this. Cover crop biomass amount, CC residue management, and the amount of residues from the primary crops will determine the extent to which CCs can affect soil temperature.

Changes in Greenhouse Gas Fluxes

What happens to soil C and N gas fluxes following CC adoption? Studies assessing CO_2 and CH_4 fluxes as affected by CCs are few, but they have generally found no effects of cover cropping (Liebig et al., 2010; Sanz-Cobena et al., 2014). Although most studies have reported no effects of CCs on N_2O fluxes, a few studies have found increased N_2O fluxes with CCs (Table 4). The stimulation of N_2O emissions in non-legume CCs can be due to increased available C for denitrifiers.

A consideration of C and N dynamics and balance (input vs. output) is needed to better understand CC effects on greenhouse gas (GHG) fluxes. For example, legume CCs can indirectly reduce N_2O fluxes by reducing inorganic fertilizer and manure application requirements for the primary crops. Also, because CCs often reduce NO_3 leaching, the increased N_2O fluxes with CCs can be offset by the reduction in NO_3 leaching and indirect losses of N_2O in streams, lakes, and drainage systems (Petersen et al., 2011). Thus, CCs potentially reduce total N emissions from agricultural lands.

Cover crop effects on GHG fluxes depend on various management factors including N fertilization (Jarecki et al., 2009; Mitchell et al., 2013), tillage system (Petersen et al., 2011), CC species (Rosecrance et al., 2000), and irrigation management (Kallenbach et al., 2010), among others. First, CCs can minimize N_2O losses, but high rates of inorganic N fertilization of primary crops or animal manure application can override this benefit (Jarecki et al., 2009). Emissions of N_2O commonly increase with an increase in N fertilization rates. Mitchell et al. (2013) found that a rye crop reduced N_2O fluxes when no fertilizer was applied to a no-till corn–soybean rotation, but it increased N_2O fluxes when N fertilizer was applied. Second, soil gas fluxes between legume and non-legume CCs differ. Some scientists suggested that legume CCs increase N_2O fluxes relative to a control due to the release of N from legumes when incorporated into the soil (Rosecrance et al., 2000). Emissions of N_2O from the soil after legume residue input can be thrice that without legume residue input (Garcia-Ruiz and Baggs, 2007). Third, GHG fluxes under CCs can vary with the amount of tillage used to incorporate them into the soil. Petersen et al. (2011) found that forage radish increased N_2O fluxes under conventional tillage more than under no-till and reduced tillage, suggesting that increased soil disturbance during CC termination reduces the benefits of CCs for mitigating N_2O fluxes. Fourth, irrigation practices affect the rates of GHG fluxes. Kallenbach et al. (2010) reported that CO_2 and N_2O fluxes from hairy vetch and Austrian winter pea CCs were greater under furrow irrigation than under subsurface drip irrigation in a tomato (*Lycopersicon esculentum* L.) row-crop system in California, probably due to drier soils under drip irrigation than under furrow irrigation.

Cover crops can reduce N_2O fluxes by competing with microorganisms for available N and reducing NO_3 leaching, but they can increase N_2O fluxes after termination due to biomass decomposition. Therefore, the resulting cumulative fluxes for the entire growing season between CC and no-CC treatments do not often differ (Mitchell et al., 2013). In Michigan, Fronning et al. (2008) found that fields with winter rye CCs had lower N_2O fluxes in May, higher fluxes in June, and no differences from July to October relative to no-CC treatments.

In general, CCs appear to have small or no effects on GHG fluxes (Table 4). Cover crops can increase CO_2 fluxes when CC residues decompose. Accounting for all the factors that affect C and N budgets (inputs vs. outputs) is needed to assess the overall impact of cover cropping on mitigating GHG fluxes from croplands. Considering the positive effects of CCs on increasing N uptake and reducing N leaching, CCs are a potential strategy for reducing cumulative N emissions from soils as long as fertilizer N inputs are matched to crop needs in quantity and timing.

Table 3. Cover crop (CC) effects on water infiltration in different studies.

Study site	Precipitation	Soil texture	Tillage	Crop	Cover crop planting time	Time after experiment start	Cover crop treatments	Cumulative infiltration	Reference
	mm yr^{-1}					yr		cm	
Coastal plain, Maryland	1033	silt loam	no-till	corn	winter	13	hairy vetch	0.52b†‡	Steele et al. (2012)
							rye	1.43a	
Hesston, KS	830	silt loam	no-till	wheat–grain sorghum	summer CCs	15	no CC	5.7b	Blanco-Canqui et al. (2011)
							late-maturing soybean	11.4ab	
							sunn hemp	15.5a	
Davis, CA	500	loam	conventional tillage	tomato	winter	3	no CC	19.0b	Folorunso et al. (1992)
							oat/vetch	20.3a	
							oat	21.1a	
Ceres, CA	333	sandy loam	conventional tillage	orchard	all year	5	no CC	3.3b	Folorunso et al. (1992)
							bromegrass (*Bromus inermis* Leyss.)	6.6a	
							strawberry clover (*Trifolium fragiferum* L.)	6.3a	

† Means followed by different lowercase letters in a column within the same study or location are significantly different at $p < 0.05$.

‡ Water infiltration rate (mm s^{-1}) averaged across two seasons.

Table 4. Cover crop (CC) effects on N_2O-N fluxes across different soil types, tillage systems, crops, and cover crop species.

Study site	Soil	Tillage	Crop	N rates	Time after experiment start	Cover crop treatments	N_2O-N	Reference
				kg ha^{-1}	yr		kg ha^{-1}	
Aranjuez, Spain	Typic Calcixerept	no-till	corn	210	1	no CC	0.17ns†	Sanz-Cobena et al. (2014)
						Barley	0.16	
						Vetch	0.17	
						Rapeseed	0.24	
Boone County, Iowa	loam	no-till	corn	0	0.5	no CC	1.6c‡	Mitchell et al. (2013)
				0		winter rye	1.1c	
				135		no CC	3.0b	
				135		winter rye	4.8a	
				225		No CC	5.1a	
				225		winter rye	5.2a	
Carlow, Ireland	sandy loam	moldboard plow	spring barley	0	1.5	no CC	0.86b	Abdalla et al. (2012)
				70		no CC	1.37a	
				140		no CC	1.74a	
		reduced tillage		0		mustard	0.87b	
				70		mustard	2.17a	
				140		mustard	2.42a	
Denmark	Mollic Luvisol	no-till, reduced tillage, moldboard plow	spring barley	100	0.5	no CC	1.71b	Petersen et al. (2011)
						fodder radish	3.02a	
Mandan, ND	silt loam	no-till	spring wheat	67 + 34	1.5	CC	1.8ns	Liebig et al. (2010)
			spring wheat–safflower			rye	1.8	
Ames, IA	silty clay loam & loam	no-till	soybean–corn	175	1	no CC	7.6ns	Jarecki et al. (2009)
						rye	5.2	
East Lansing, MI	sandy loam & loam	no-till	corn–soybean	urea–NH_4NO_3	3	no CC	1.96ns	Fronning et al. (2008)
						winter rye	1.39	
Hickory Corners, MI	Typic Hapludalfs	no-till	corn–soybean–wheat	123 + 56	8	no CC	1.27ns	Robertson et al. (2000)
		moldboard plow		123 + 56		no CC	1.18	
		low input		37 + 17		legume	1.36	
		organic		0		legume	1.27	

† ns, not significant at $p < 0.05$.

‡ Means followed by different lowercase letters in a column within the same study or location are significantly different at $p < 0.05$.

Managing Nutrients

The effects of CCs on soil nutrients, particularly N, have been previously reviewed (Dabney et al., 2001, 2010; Cherr et al., 2006; Blanco-Canqui et al., 2011; Kaspar and Singer, 2011; and others). For example, Dabney et al. (2010) reviewed this subject for four regions in the United States including the humid South, the humid North and Corn Belt, the Northern Plains, and the irrigated West. Thus, in this review, we provide only a short summary of CC effects on nutrient dynamics.

Cover crops primarily affect soil nutrient dynamics and balance by (i) fixing atmospheric N_2, (ii) scavenging nutrients, (iii) reducing nutrient leaching, and (iv) reducing nutrient erosion. Including CCs in intensively managed agroecosystems could thus affect nutrient accumulation, recovery, storage, and cycling. For example, legume CCs can symbiotically fix N_2 and supply significant amounts of N in low-fertility soils, thereby supplementing N for the next crop and reducing N application requirements. A study in eastern Kansas found that, after four rotation cycles, soil total N increased by 258 kg ha^{-1} under late-maturing soybean and by 279 kg ha^{-1} under sunn hemp compared with non-CC plots when both legume CCs were planted after each winter wheat harvest in a winter wheat–grain sorghum rotation (Blanco-Canqui et al., 2011). Others also found high N contributions from leguminous CCs (Reddy et al., 1986; Mansoer et al., 1997).

The C/N ratio of legume CCs is <20 (Dabney et al., 2001), which favors rapid residue decomposition and N mineralization relative to grass CCs, which have greater C/N ratios. Incorporation of CC residues into the soil accelerates N mineralization, but this practice buries CC residues and reduces their benefits of protecting the soil surface. Summer legume CCs can have greater effects on soil N than winter legume CCs because summer legumes can grow rapidly in late summer and fall, producing large amounts of biomass and returning high amounts of N-enriched biomass (Wang et al., 2009; Blanco-Canqui et al., 2011). In some cases, winter legume CCs do not increase soil N, particularly in <5 yr (Sainju et al., 2003; Villamil et al., 2006).

Cover crops can also reduce the potential for NO_3 leaching. Kaspar and Singer (2011) summarized CC-induced reductions in NO_3 leaching losses for 16 studies and found that the reduction in leaching losses ranged from 6 to 94% under different CCs including rye, hairy vetch, oat, winter wheat, mustard (*Brassica* spp.), purple vetch (*Vicia benghalensis* L.), and ryegrass (*Lolium multiflorum* L.). Recently, a global meta-analysis of strategies to control NO_3 leaching in irrigated agricultural systems found that the inclusion of non-leguminous CCs reduces NO_3 leaching by about 50% compared with fallow in irrigated cropping systems (Tonitto et al., 2006; Quemada et al., 2013). On sandy loams in southwestern Michigan, a rye CC interseeded with inbred corn receiving N at 202 kg N ha^{-1} sequestered from 46 to 56 kg ha^{-1} of excess N (Rasse et al., 2000). Also, recent estimates have indicated that haying CCs reduces NO_3 leaching more than non-haying practices (Gabriel et al., 2013). In cool and wet soils, water use by CCs is beneficial to reduce the potential for leaching when the soil profile is full of water.

The use of subsurface tile drainage is essential to increased crop production in some areas, but it usually contributes to nutrient loss from the root zone and thus pollution of surface waters if not properly managed. The inclusion of CCs retains nutrients in the root zone and reduces their losses from fields with subsurface tile drains. In Iowa, a winter rye CC reduced the NO_3 concentration in tile drainage by 48% over 5 yr, while a fall oat CC reduced the NO_3 concentration by 26% in corn and soybean fields (Kaspar et al., 2012). In southwestern Minnesota, across 3 yr, a winter rye CC after corn in corn–soybean systems reduced NO_3 concentrations in tile drainage by 13% relative to a system without CCs (Strock et al., 2004).

Cover crops scavenge NO_3 and other nutrients and convert them to organic N compounds, reducing excess nutrients available for erosion and leaching. Either grass or brassica CC species are more effective than legume CCs at absorbing and immobilizing N (Dabney et al., 2001). Grass CCs primarily scavenge nutrients, while legume CCs fix N_2 from the atmosphere. Scavenged nutrients are released slowly and gradually after termination, which reduces nutrient losses and improves nutrient use efficiency relative to rapidly soluble N from inorganic fertilizers.

Cover crop termination dates directly affect the N supply in the soil for the following crop. If CCs are terminated late or at full maturity, soil N can still be immobilized and not readily available for the subsequent crop regardless of CC species (Dabney et al., 2001; Schomberg et al., 2007). This can result in reduced crop yields if sufficient N is not supplied to the crops and they do not fix N_2. Nutrient immobilization is greater in systems with low precipitation input, fine-textured soils, no-till management, and late termination of CCs.

Microbial activity contributes to rapid (<8 wk) mineralization of CC-derived N if other factors such as soil water content and temperature are favorable (Jackson, 2000). Cover crops can boost soil arbuscular mycorrhizal fungal activity, which directly contributes to nutrient absorption and availability (Dabney et al., 2001). Microbial activity is the primary link between soil organic matter and nutrient availability to plants. The influence of microbial activity on nutrient availability can be greater in no-till than in plowed soils due to the lack of disturbance near the rhizosphere in no-till soils.

Cover crops can also absorb and convert available P into organic forms, reducing the P concentration in the soil. For example, in Illinois, Villamil et al. (2006) found lower soil P concentrations under corn–rye/soybean–rye and corn–rye/soybean–hairy vetch and rye sequences than in a corn–soybean rotation without CCs. Other studies have also found that CCs reduce available soil P (Hargrove, 1986) or have no consistent effects (Eckert, 1991). Brassicas can strongly take up N relative to other cover crop species (Kristensen and Thorup-Kristensen, 2004). The increased nutrient uptake by CCs can be important to manage excess nutrient additions to the soil from animal manure or fertilizers and minimize the risk of water pollution.

As discussed above, CCs are effective at reducing water erosion. Thus, CCs can reduce sediment-associated losses of nutrients (N, P, and others) from agricultural lands. Cover crops not only hold essential nutrients in place for the primary crops but also reduce the nutrient load entering downstream waters, reducing the risk of nonpoint-source pollution (Kovar et al., 2011). Most nutrient losses due to erosion and leaching occur in the period between harvest and planting of primary crops. Growing CCs during this period, especially in springtime when primary crops are not taking up nutrients and the chances for precipitation are high, can reduce nutrient losses (Kovar et al., 2011). The addition of CCs can be a means to minimize losses of nutrients in runoff when residue cover is insufficient.

An additional source of background information on nutrient relations in CCs interacting with primary crops is from the extensive literature on intercropping cereals and legumes (Francis, 1986). Facilitation of nutrient uptake in corn/faba bean (*Vicia faba* L.) intercrops compared with sole cropping of each species has been reported; up to 20% greater N uptake was measured along with some higher uptake in P in this common crop combination in China (Li et al., 2003). There are other reports of a cereal intercropped with a legume acquiring some of its N from the associated legume (Midmore, 1993; Stern, 1993). A report on the complementarity of root architecture among different crops helps explain its advantage over monocultures (Postma and Lynch 2012). The complex interspecific interactions warrant more research and consideration of nutrient relations between CCs and annual crops growing in association.

The use of CCs seems to alter soil organic C, N, and P concentrations more than other chemical properties, including pH and soil gas concentrations. Cover crops reduce (Hargrove, 1986) or have no effect on soil pH (Eckert, 1991; Mullen et al., 1998; Jokela et al., 2009). The abundant literature indicates that CCs increase nutrient concentrations in the soil not only by capturing nutrients (i.e., atmospheric N_2) but also by reducing losses of nutrients due to leaching and soil erosion. Cover crops also improve nutrient use efficiency and reduce the risk of water pollution. The benefits of CCs for sequestering, scavenging, and supplying some of the available N needs to the main crop are especially important in soils with low organic matter content.

Improving Soil Microbial Environment and Wildlife

Increases in populations of soil macro- and microorganisms are dynamic indicators of improvement in both soil properties and overall soil ecosystem services. In a rainfed winter wheat–grain sorghum rotation, the addition of hairy vetch during the first rotation cycles and sunn hemp and late-maturing soybean summer CCs after wheat harvest increased the number of earthworms (*Lumbricus terrestris* L.) by sixfold compared with plots without summer CCs in eastern Kansas after 15 yr (Blanco-Canqui et al., 2011). An increase in earthworm population is positively associated with increases in water infiltration and soil aggregate stability (Willoughby and Kladivko, 2002; Blanco-Canqui et al., 2011).

Cover crops also positively affect the soil microbial community structure and microbial properties and processes. In North Carolina, Kirchner et al. (1993) found that a crimson clover CC in a conventional tillage, continuous corn system increased microbial biomass C, heterotrophic bacteria numbers, and soil enzyme activities (alkaline phosphatase, arylsulfatase, and β-glucosidase). Similarly, in Washington, under a winter wheat–spring pea rotation, Bolton et al. (1985) reported that the addition of Austrian winter pea CC green manure increased microbial numbers, microbial biomass C, and significantly increased enzymatic activities (urease, phosphatase, and dehydrogenase activities) compared with the same rotation without CCs. In Tennessee, Mullen et al. (1998) found that a hairy vetch CC increased bacterial numbers and enzymatic activities (acid phosphatase, arylsulfatase, β-glucosidase, and L-asparaginase), but a winter wheat CC had no effect when the CCs were grown each year after corn. The increase in microbial activity under CCs is strongly and positively correlated with an increase in soil organic C (Mullen et al., 1998). Changes in soil microbial biomass, microbial community structure, fungal biomass, and fungal hyphal biomass and necromass under CCs affect other soil processes such as aggregation. Cover crop termination method and early-spring plant communities impacted the soil microbial community composition of an organic cropping system in eastern Nebraska (Wortman et al., 2013a).

The addition of CCs after crop residue removal for expanded uses can counteract the possible reductions in the soil microbial community after residue removal. At four US locations with contrasting soil-climatic conditions, Lehman et al. (2014) found that CCs minimized the reduction in microbial population that occurs in soil microbial communities after crop residue removal. Planting CCs can be particularly useful to protect the soil after excessive residue removal, such as corn silage harvest, that exposes the soil surface to rapid physical, chemical, and biological changes. Thus, planting CCs can provide cover and food to soil organisms, enhancing the soil microbial community. In a 2-yr study in Ohio, an annual ryegrass CC and a mixture of winter rye and oat CCs increased the soil microbial biomass when planted after corn silage in 1 of 2 yr compared with the control in the 0- to 15-cm soil depth (Fae et al., 2009).

Cover crops can improve the microbial biomass by increasing the root biomass concentration (Fae et al., 2009). Cover crops can increase arbuscular mycorrhizal fungi, which interact with living CC roots (Lehman et al., 2014). No-till with reduced soil disturbance and the presence of surface residue cover enhances this relationship. The increased CC root biomass correlates with increased microbial biomass (Fae et al., 2009; Lehman et al., 2014).

Cover crops can also enhance wildlife habitat and diversity, which are indicators of healthy ecosystems. For example, CCs provide habitat for beneficial insects and birds. They have a greater positive effect on bird and insect populations in conventionally tilled fields than in no-till fields due to limited or no residue cover in tilled fields (Golawski et al., 2013). Cover crops diversify cropping systems and add beneficial complexity and intensity to traditional rotations, thereby providing valuable shelter, food, and nesting opportunities for birds and other wildlife species when primary crops are absent. In eastern Kansas, in conventional tillage grain sorghum plots, Robel and Xiong (2001) found that a sweetclover (*Melilotus officinalis* L.) CC increased the invertebrate biomass compared with plots without CCs. The same study found that sweetclover was more beneficial to wildlife than rye or hairy vetch CCs. In California, Smallwood (1996) reported that CCs attracted predatory vertebrates, which enhanced farm aesthetics and reduced animal damage. Cover crops provide a food source to wildlife during times when primary crops are absent. The extent to which CCs enhance wildlife habitat warrants further study for different climates, CC species, tillage and cropping systems, single species and multispecies mixes, seeding rates, termination dates, termination methods, and others.

Suppressing Weeds

Cover crops can be a useful means to suppress weeds within agroecosystems (Mirsky et al., 2011; Teasdale et al., 2007). However, there seems to be a great deal of variation in the reported success of using CCs for weed suppression. This variation is a result of the complexity of agroecosystems. Different weed species in different environments respond differently to CCs depending on the CC species planted. Moreover, how and when the CC is grown, how much it grows, how rapidly it decomposes, the method of its termination, and other management practices influence its potential impact on weed populations.

There are two ways that CCs can influence weed populations (Teasdale et al., 2007). One is through direct competition with growing weed species. This kind of CC is generally referred to as a *smother crop* or *living mulch*. The second approach uses indirect suppression resulting from physical (Teasdale et al., 1991; Teasdale and Mohler, 2000) or chemical suppression (Weston and Duke 2003) or manipulation of nutrient cycles. Cover crop–weed competition can be inferred from data on multiple crop effects on weed species (Francis, 1986). Studies of the mechanisms of weed management through cropping system design provide a foundation for research on CC and crop interactions.

Cover crops planted with the primary crop will generally provide weed suppression through competition for light, soil water, and nutrients (Teasdale et al., 2007). A potential negative effect is that the CC will also be competing with the crop. As such, the goal is to identify a CC species that is short lived, grows actively, but is also short enough not to compete with the crop for light. An adequate soil water supply is necessary to minimize CC–primary crop competition for water.

Leguminous CCs are often used because they will compete less for soil N (Sarrantonio and Gallandt, 2003).

Where CCs compete directly with weed species, a common measure of CC success is the relationship between the weed biomass and the CC biomass. Multispecies CC systems have recently garnered considerable attention (Smith et al., 2015; Wortman et al., 2013b). Originally, this interest stemmed from the diversity–invasibility hypothesis (Elton, 1958), which postulates that diverse plant communities should be more resistant to invasion than less diverse communities, in part because a diverse community will be more productive overall. Indeed, Wortman et al. (2012b) found that diverse mixtures of spring-sown CCs produced more biomass than less diverse CCs. Recently, Smith et al. (2015) pointed out that functional and morphological traits of a given CC species can be a more important determinant of its success in suppressing weeds than productivity per se. They outlined an interesting methodological framework to evaluate the influence of functional group diversity relative to CC species diversity on weed suppression based on community assembly theory.

More commonly, CCs are planted during a fallow period. In such cases, the CC provides weed suppression via the residue left after termination or by outcompeting weeds that would otherwise produce seed and increase the potential for weed–crop competition in the succeeding cropping cycles. Cover crop residue can affect weeds by physically modifying the microenvironment (Teasdale and Mohler, 2000), by releasing leachates from residue that chemically interfere with weeds or soil microbial populations that benefit weedy species (Bhowmik and Inderjit, 2003; Weston, 1996), or by affecting nutrient cycling in such a way as to make nutrients temporarily unavailable to emerging weeds.

In temperate regions, fall-sown winter annuals are a common choice for CCs because they provide many benefits before termination (Blackshaw et al., 2008; Dabney et al., 2001). Especially in geographic regions where soil water is not a limiting factor, cereal rye is popular because it produces large quantities of biomass that subsequently provides substantial physical suppression of weeds (Davis, 2010; Ryan et al., 2011) and also contains some allelopathic compounds (Reberg-Horton et al., 2005) that suppress weeds. However, rye has also been used in drier climates such as the northern Great Plains (Blackshaw et al., 2008; Williams et al., 2000).

Establishing a winter annual CC following corn or soybean can be difficult owing to the late harvest of these summer crops in the more northern parts of the US Midwest (Wortman et al., 2012a). Frost-seeded or spring-sown CCs can provide flexibility under these circumstances. Wortman et al. (2013b) evaluated the effects of frost-seeded brassica and legume species and their termination method on weed suppression in soybean in Nebraska and found mixed results depending on the year. Most importantly, they found that the method of termination had the greatest effect on weed suppression. The use of a sweep-plow undercutter allowed subsequent weed suppression, whereas disking generally enhanced weed growth.

The literature indicates that CCs can suppress weeds. The effectiveness of CCs for suppressing weeds will depend on CC management and CC species. Cover crops primarily suppress weeds through (i) direct competition with weeds for resources and (ii) physical and chemical suppression. Growing CCs can be more effective than CC residues because living CCs compete with weeds for light, water, and nutrients. A better understanding of CC–weed interactions and allelopathic effects for different CC species, management systems, and climates is needed.

Managing or Conserving Soil Water

Cover crops have positive, negative, or neutral effects on the soil-profile distribution of water, depending on soil type and climatic region (Unger and Vigil, 1998). Cover crops use soil water and, in the long term, improve water infiltration and related soil structural and hydraulic properties. These attributes of CCs can improve drainage and eliminate excess water on poorly drained soils or in regions with high average precipitation and low evapotranspiration rates. For example, in Manitoba, Canada, a region with a mean annual precipitation of 589 mm and an evapotranspiration rate ranging from 250 to 350 mm, Kahimba et al. (2008) found that berseem clover CCs increased deep percolation, reduced excess soil moisture, allowed earlier planting, and increased crop production. In particular, no-till soils with a residue mulch can be cooler and wetter in spring in cold and wet climates, as discussed above. The presence of CCs can increase water infiltration and soil drying in these climates.

In water-limited or semiarid regions, growing CCs can, however, reduce the water available for the next crop (Unger and Vigil, 1998; Nielsen and Vigil, 2005; Nielsen et al., 2015). The potential adverse effects of CCs on plant-available water and crop yields following CCs often limit the adoption of CCs in semiarid regions. For example, in Akron, CO, a region with a mean annual precipitation of 421 mm, Nielsen and Vigil (2005) reported that spring legume CCs planted during the fallow period in a winter wheat–fallow system reduced soil water at wheat planting by 55 mm when the legumes were terminated early and by 104 mm when they were terminated late, reducing wheat yields relative to fallow plots without CCs under conventional tillage. They terminated the CCs at 2-wk intervals starting in June and planted wheat in September. Other studies in the Great Plains including those in Garden City, KS (Holman et al., 2012), and Bozeman, MT (Burgess et al., 2014), have, however, reported that despite the reduced soil water content with CCs, subsequent crop yields did not decrease.

While growing CCs generally reduces the water available for the subsequent crops, CCs also reduce water losses by reducing runoff, increasing water infiltration, and improving other physical processes (Blanco-Canqui et al., 2012). Cover crop roots and surface residues generally improve soil aggregation and soil macroporosity, which increase rain or irrigation water infiltration. Residues left on the soil surface after CC termination contribute to soil water storage by reducing evaporation. Moreover, in the long term, increases in the soil organic C concentration under CCs, particularly in soils with an initial low C concentration or low fertility, can reduce some of the negative effects of CCs on soil water storage because organic C enhances the ability of a soil to absorb and retain water due to its high water adsorptive capacity or high specific surface area. The soil organic C concentration is positively correlated with soil water storage and retention capacity (Rawls et al., 2003; Blanco-Canqui et al., 2013b).

Early termination of CCs before planting the primary crop is a potential strategy to reduce some of the adverse effects of CCs on water storage if sufficient precipitation occurs between termination and planting of the primary crops. Changes in soil temperature due to growing CCs or residues affect soil water storage. As mentioned above, CCs reduce daytime soil temperatures, which can reduce excessive evaporation and maintain the soil water content compared with bare soils. Soil water content under CCs increases as soil temperature decreases (Steenwerth and Belina, 2008). Unger and Vigil (1998) previously discussed CC effects on soil water relationships for humid, subhumid, and semiarid regions.

In regions with high precipitation inputs (>800 mm), CCs often increase the soil water content and can benefit crop production, particularly in dry years. In south-central Kansas, the soil volumetric water content under summer CCs was greater by an average of 35% than in plots without CCs for the 0- to 20-cm soil depth when the soil water content was measured in early spring when the CCs were terminated the previous fall. The greater soil water content under summer CCs was negatively and highly correlated ($r = -0.79$, $P < 0.001$) with the lower soil temperature under CCs (Blanco-Canqui et al., 2011). Cover crops can maintain or increase soil water storage in the Corn Belt during severe or extreme drought years. During the drought of 2012, Daigh et al. (2014) reported that rye CCs either had no adverse effect or increased soil water storage across various sites in Iowa and Indiana. Early termination of CCs is recommended to reduce water depletion in dry years in regions of high average precipitation, but in semiarid regions even early termination may not offset the soil water depletion for the primary crops, particularly in years with below-average precipitation. As indicated above, in cool and wet soils, water use by CCs is beneficial to increase the storage available for future precipitation and reduce runoff losses. Finally, it is important to consider that while CCs reduce soil water storage in water-limited regions, they also improve soil physical, chemical, and biological processes and properties, which positively contribute to long-term soil productivity as well as environmental quality.

Improving Crop Yields

Cover crop impacts on subsequent crop yields vary. Cover crops increase, reduce, or have no effects on subsequent crop yields (Table 5; Kuo and Jellum, 2000; Andraski and Bundy, 2005; Balkcom and Reeves, 2005; Olson et al., 2010). Table 5 shows that out of 17 studies, CCs increased subsequent crop yields in nine, had no effect in six, and reduced yields in two studies. Their impacts on crop yields depend on annual precipitation, CC species (legume vs. non-legume CCs), growing season (summer vs. winter CCs), tillage system (no-till vs. conventional tillage), and number of years of CC management.

Precipitation amount is one of the leading factors that affects the performance of CCs and their impacts on subsequent crops. In a review, Unger and Vigil (1998) suggested that CCs can better fit in humid and subhumid regions than in semiarid regions where precipitation is limited. In regions with high precipitation, CCs increase or have no effect on crop yields. In water-limited regions such as the semiarid central Great Plains, CCs can reduce crop yields, depending on site-specific conditions including the evapotranspiration rate and tillage management (Schlegel and Havlin, 1997; Nielsen and Vigil, 2005; Holman et al., 2012; Burgess et al., 2014). In Akron, CO, a region with a mean annual precipitation of 421 mm, Nielsen and Vigil (2005) reported that Austrian winter pea, spring field pea, black lentil, and hairy vetch CCs grown in spring during the fallow period in a winter wheat–fallow system reduced wheat yields under conventional tillage. A recent study comparing single species vs. a mixture containing 10 species in Akron, CO, and Sidney, NE, found that CC water use following a dry year reduced subsequent wheat yield, but in the following year, with above-average precipitation, there was no yield difference due to no difference in soil water storage (Nielsen, el al, 2015).

Other studies in the Great Plains have, however, reported that CCs do not always reduce subsequent crop yields, suggesting that CC effects on crop yields in water-limited regions vary with site-specific conditions such as annual precipitation amount and evapotranspiration rates.

In Garden City, KS, a region with a mean annual precipitation of 489 mm, Holman et al. (2012) found that winter and spring CCs and forage crops grown in place of fallow in a no-till winter wheat–fallow system did not reduce the wheat yield but a winter triticale CC did reduce yields compared with fallow plots without CCs under no-till management when the CCs were terminated between 15 May and 1 June. They concluded that, in general, fallow periods in winter wheat–fallow systems can be shortened by using cover or forage crops with no risk of reducing yields. Similarly, in Bozeman, MT, a region with a mean annual precipitation of 356 mm, Burgess et al. (2014) found that early termination of spring-planted annual legume CCs such as pea and lentil, when used as green manure, did not reduce wheat yields. These few studies from semiarid regions suggest that, while CCs do not always reduce crop yields, they do not increase crop yields in these regions. Thus, an economic return from CCs can be limited in semiarid regions unless the CCs are grown as forage crops for haying or grazing. The evapotranspiration rate is another factor that can influence CC effects on crop yields in the Great Plains. Under the same amount of precipitation in semiarid regions, CC performance will decrease with an increase in the evapotranspiration rate (Nielsen and Vigil, 2005; Burgess et al., 2014). In the Great Plains, evapotranspiration rates, in general, increase from north to south.

Studies from regions with higher precipitation indicate that CCs can increase crop yields (Kuo and Jellum, 2000; Andraski and Bundy, 2005; Balkcom and Reeves, 2005; Blanco-Canqui et al., 2012; Table 5). For example, in south-central Kansas, a region with a mean annual precipitation of 878 mm, sunn hemp and late-maturing soybean as summer legume CCs increased crop yield when managed under a no-till winter wheat–grain sorghum rotation, particularly at low rates of inorganic N application (Blanco-Canqui et al., 2012). Sunn hemp increased the grain sorghum yield by 1.43 Mg ha^{-1} at 0 kg N ha^{-1}, by 0.67 Mg ha^{-1} at 33 kg N ha^{-1}, and by 0.58 Mg ha^{-1} at 100 kg N ha^{-1}, while it increased the wheat yield by 0.27 Mg ha^{-1} at $\leq$66 kg N ha^{-1} relative to plots without CCs. These results indicate that CC benefits for increasing crop yield decreased with increasing rates of inorganic N fertilizer. Also, a meta-analysis of 36 studies found that crop yield benefits of legume CCs decrease with high rates of N fertilization (Miguez and Bollero, 2005).

Table 5. Cover crop (CC) effects on grain yield across different precipitation zones, soil types, tillage systems, and cover crop species.

Study site	Precipitation	Soil texture	Tillage	Cropping system	Cover crop planting time	Time after experiment start	Cover crops	Grain yield	References
	mm					yr		Mg ha^{-1}	
Shorter, AL	1560	loamy sand	conventional tillage	corn	winter	1	no CC	5.2b†	Balkcom and Reeves (2005)
							sunn hemp	6.9a	
						2	no CC	5.7b	
							sunn hemp	6.9a	
						3	no CC	6.3ns	
							sunn hemp	6.9	
Beltsville, MD	1192	gravelly loam	no-till	corn	winter		no CC	7.7bc	Decker et al. (1994)
							hairy vetch	8.7a	
						1	winter pea	8.9a	
							crimson clover	8.1ab	
							Wheat	7.2c	
Saratoga, NC	1190	loamy sand	no-till and chiseled	corn	winter	1	no CC	6.0a	Ewing et al. (1991)
							crimson clover	5.5b	
Rocky Mount, NC	1190	sand	no-till and chiseled	corn	winter	2	no CC	3.6a	
							crimson clover	2.7b	
Georgetown, DE	1150	loamy sand	no-till	corn	winter	1	no CC	4.4d	Mitchell and Teel (1977)
							spring oats	4.7bcd	
							spring oats + hairy vetch	5.6a	
							spring oats + crimson clover	5.5ab	
							rye	4.5cd	
							rye + hairy vetch	5.7a	
							rye + crimson clover	5.3abc	
Ellicott City, MD	1064	silt loam	no-till	corn	winter	across 3 yr	no CC	6.7bc	Decker et al. (1994)
							hairy vetch	7.2ab	
							winter pea	7.5a	
							crimson clover	7.2ab	
							wheat	6.2c	
Urbana, IL	1050	silty clay loam	conventional tillage	soybean	fall	1	no CC	3.5ns	Acuna and Villamil (2014)
							CCs	3.5	
South Charleston, OH	1033	silt loam	no-till	corn	winter	2	no CC	11.1ns	Henry et al. (2010)
							red clover	11.7	
						3	no CC	9.2ns	
							red clover	9.3	
Pana, IL	1030	silty clay loam	conventional tillage	corn	winter	across 4 yr	no CC	10.8b	Maughan et al. (2009)
							spring oats and cereal rye	11.5a	
Poplar Hill, MD	1009	silt loam	no-till	corn	winter	across 3 yr	no CC	6.3b	Decker et al. (1994)
							hairy vetch	8.9a	
							winter pea	8.4a	
							crimson clover	8.7a	
							wheat	6.9b	
Rock Springs, PA	1006	silt loam	no-till	corn	winter	3	no CC	9.70ns	Duiker and Curran (2005)
							rye	10.02	

continued on next page

Table 5.(cont.).

Study site	Precipitation	Soil texture	Tillage	Cropping system	Cover crop planting time	Time after experiment start	Cover crops	Grain yield	References
Columbia, MO	992	silt loam	no-till	corn	winter	across 3 yr	no CC	4.83abcd	Reinbott et al. (2004)
							oat	4.56cd	
							hairy vetch	5.06ab	
							Austrian winter pea	5.19a	
							hairy vetch + oat	4.88abcd	
							winter pea + oat	4.47d	
				sorghum			no CC	6.59b	
							oat	6.57b	
							hairy vetch	7.33a	
							Austrian winter pea	7.06ab	
							hairy vetch + oat	6.94ab	
							winter pea + oat	6.64b	
Zaragoza, Spain	962	silt loam	conventional tillage	corn	winter	1	no CC	16.9ns	Salmerón et al. (2010)
							barley	13.9	
							winter rapeseed	14.2	
							vetch	17.8	
						2	no CC	16.4a	
							barley	13.8b	
							winter rapeseed	13.8b	
Hoytville, OH	859	clay loam	no-till	corn	winter	2	no CC	6.2b	Henry et al. (2010)
							red clover	7.3a	
						3	no CC	7.3ns	
							red clover	7.9	
						1	no CC	10.55ns	Andraski and Bundy (2005)
							oat	9.91	
							triticale	10.69	
							rye	10.47	
							rye removed	10.59	
Hancock, WI	769	loamy sand	conventional tillage	corn	winter	2	no CC	7.02b	
							oat	8.64a	
							triticale	7.92ab	
							rye	8.25a	
							rye removed	8.18a	
						3	no CC	8.74c	
							oat	10.26ab	
							triticale	10.46ab	
							rye	10.83a	
							rye removed	9.98b	
Andover, SD	602	loam	no-till	corn	fall	1	no CC	13.39ns	Reese et al. (2014)
							CC mix	13.02	
						2	no CC	11.83a	
							CC mix	10.07b	
Akron, CO	428	silt loam	no-till	wheat	summer	Across 6 yr	no CC	3.92a	Nielsen and Vigil (2005)
							winter pea or field pea	2.64b	
Trail City, SD	414	loam	no-till	corn	fall	1	no CC	6.90ns	Reese et al. (2014)
							CC mix	7.66	

† Means followed by different lowercase letters in a column within the same study or location are different at $P < 0.05$; ns, not significant.

Studies on the effect of CC mixtures on crop yields are few but suggest that their effects on the subsequent crop yield do not differ from single CC species (Table 5). In eastern Nebraska, spring-planted mixtures of legume and brassica CC mixtures (two, four, six, and eight species) and CC termination methods (disk and undercutter) under a sunflower (*Helianthus annuus* L.)–soybean–corn rotation for 3 yr did not affect crop yields, but termination of the CCs with the undercutter increased the corn yield by 1.40 Mg ha^{-1} and the soybean yield by 0.88 Mg ha^{-1} (Wortman et al., 2012b). Similarly, in southeastern New Hampshire, a mixture of legume, broadleaf, and brassica CC species and each species grown as a monoculture did not affect the performance of the next oat cash crop in a 2-yr study (Smith et al., 2014). Most studies have reported a significant CC vs. year interaction, which suggests that long-term (>3 yr) studies are needed to better discern the effects of monocultures and CC mixtures on primary crop yields and soil properties. Some studies have reported that while CCs do not increase crop yields in the first year, they have positive effects as time progresses (Decker et al., 1994; Andraski and Bundy, 2005).

High-N_2–fixing (i.e., legume) CCs can have more rapid and greater effects on increasing crop yields than CCs with low or no N_2–fixing capacity. Specifically, summer legume CCs are more effective at increasing crop yields than winter CCs because of higher potential biomass and N inputs in fall (Mansoer et al., 1997; Schomberg et al., 2007). For example, a sunn hemp summer CC produced 7.6 Mg ha^{-1} of biomass with 144 kg ha^{-1} of N in the first 2 yr and increased corn yield by 1.2 Mg ha^{-1} relative to non-CC plots in 2 of 3 yr of management on a loamy sand in Alabama (Balkcom and Reeves, 2005). The same study found that a sunn hemp CC had no effect on corn yield in the third year. In semiarid regions in Canada, legumes planted in fall to reduce N fertilizer requirements had mixed effects (Blackshaw et al., 2010). Winter pea reduced winter wheat yield by 23 to 37%, whereas alfalfa (*Medicago sativa* L.) added 18 to 20 kg ha^{-1} of available soil N and increased the yield of the succeeding canola (*Brassica napus* L.) crop. Some researchers have indicated that corn under no-till production utilizes CC-derived N more efficiently than corn under conventional tillage (Zhang and Blevins, 1996), which suggests that leaving CC residues on the surface not only protects the soil but, in some cases, also increases CC-derived N efficiency relative to tilled systems.

Cover crops can increase crop yields in soils if they significantly increase soil organic C and soil N and improve soil properties in the long term. Blanco-Canqui et al. (2012) reported that crop yield was correlated with summer CC-induced changes in soil physical properties, concentrations of soil organic C and total N, and soil water content and temperature. The correlations were stronger at 0 kg N ha^{-1} than when inorganic N was applied. Cover crops increase, have no effect, or decrease crop yields depending on climatic conditions (Table 5), but their benefits for improving the soil or reducing soil erosion are more consistent. Precipitation and evapotranspiration appear to be the main factors that determine CC effects on subsequent crop yields. The variable effects of CCs on crop yields warrant more comprehensive research under different climates and during extended periods of CC use.

Producing Animal Feed

Grazing of CCs can be another benefit. While CCs by definition are not intended to be grazed or harvested, interest is growing in the potential side benefits of CCs in integrated crop–livestock systems, especially when the forage supply is limited (Franzluebbers and Stuedemann, 2014a). The interest in integrating CCs with livestock production is not new (Gardner and Faulkner, 1991), but the current interest is driven by increasing demands for feed and variable climatic conditions. The feed quality of pasture plants can be low, depending on the time of the year. Cover crops may provide feed of high nutritional value to enhance livestock performance at times when pasture feed quality is low (Poffenbarger, 2010). Under favorable precipitation or soil moisture conditions, growing CCs can fit for fall, winter, and spring grazing.

The impacts of CC grazing on soil properties have not been widely documented. In Georgia, Franzluebbers and Stuedemann (2008) reported that cattle grazing about 90% of the forage produced by CCs for 2.5 yr had small or no negative effects on soil physical properties in two cropping systems (corn or sorghum with a winter cereal rye CC and winter wheat with a summer pearl millet [*Pennisetum glaucum* L.] CC) under no-till and conventional tillage. They found that grazing of cereal rye and pearl millet CCs did not affect the soil bulk density or the stability of soil aggregates, but it tended to increase penetration resistance due to animal traffic and later reduced the soil water content due to increased water evaporation because CC grazing reduced the residue cover. Recently, for the same experiment in Georgia, Franzluebbers and Stuedemann (2014a) reported that grazing of CCs under both no-till and conventional tillage systems had little or no negative effects on soil C sequestration, particulate organic C, or total N compared with ungrazed CCs after 7 yr of management. Cover crop grazing and haying can reduce the beneficial effects of a surface cover on regulating soil temperature, but more experimental data are needed to document the extent to which this practice can affect soil temperature.

In southwestern Kansas, haying of winter and spring triticale CCs for 5 yr when the CCs were grown during fallow of a wheat–fallow rotation neither increased water erosion or wind erosion potential nor reduced soil organic C pools or soil aggregation compared with unharvested CCs (Blanco-Canqui et al., 2013a). The same study showed that CCs reduced soil erosion and improved soil properties compared with non-CC plots. In Ohio, Fae et al. (2009) found that grazing of annual ryegrass and a mixture of winter rye and oat managed under a no-till corn silage system increased soil penetration resistance by 7 to 15% in the first year, but 1 yr later, penetration resistance values decreased to levels similar to an ungrazed CC treatment. The same study showed that grazing of CCs did not affect the subsequent corn silage yield. Other studies have also found that grazing (Franzluebbers and Stuedemann, 2014b) or haying (Holman et al., 2012) of CCs has generally no effect on subsequent crop yields. A primary reason for the small or no negative effects of grazing can be the manure returned to the grazed fields (Poffenbarger, 2010). Better quantification of the actual nutrient removal due to grazing is needed. The results from these few studies suggest that harvesting or grazing CCs does not have rapid or large negative crop production, soil, and environmental consequences.

The adverse effects of haying CCs depend on the amount of biomass removed, the CC species grown, and the root biomass produced (Blanco-Canqui et al., 2013a). Grazing or haying CCs reduces the amount of residue left on the soil surface, but if sufficient surface cover is left (e.g., >10-cm cutting height for haying), CCs can still provide erosion control even in periods (i.e., springtime) when erosive rainstorms and strong winds are common (Blanco-Canqui et al., 2013a). Grazing or haying CCs could thus be an option to obtain some economic benefits in the short term while balancing the soil benefits of CCs (Smith et al., 2001; Martens and Entz, 2011). Under moderate grazing, CCs can contribute to the diversification of integrated crop–livestock production systems and improve economic benefits and soil productivity (Sulc and Tracy, 2007). Developing crop–livestock systems with CCs necessitates a better understanding of long-term crop, soil, and environmental responses to the new scenarios of CC management.

Producing Feedstock for Biofuel

Cover crops can contribute to the production of renewable energy. They can be part of a suite of management practices that meet the increasing demand for cellulosic biomass for biofuel production (Baker and Griffis, 2009). For one thing, CCs can ameliorate the potential adverse effects of crop residue removal for biofuel production on the soil and the environment (Blanco-Canqui, 2013). For another, they can provide cellulosic biomass as biofuel feedstock (Baker and Griffis, 2009; Feyereisen et al., 2013). In addition, they can enhance the production of dedicated bioenergy crops (i.e., perennial grasses) when used as companion or "nurse crops" (Heaton et al., 2014).

Planting CCs or forage crops after crop residue removal for biofuel production can be a potential strategy to compensate for or balance the soil N and C lost with residue removal, protect the soil from erosion, and maintain or improve soil physical, chemical, and biological properties (Blanco-Canqui et al., 2014). Because high rates of crop residue removal reduce the surface cover, growing CCs after residue removal can supplement the residue cover and provide a cover between main crops. Cover crops not only replace aboveground residue but also provide belowground or root biomass, which can be essential to hold and stabilize the soil, improve soil properties, increase microbial activity, and help maintain soil C levels. In the long term, the additional above- and belowground biomass inputs with CCs could allow greater amounts of crop residue removal for expanded uses while increasing the ecosystem services of the existing cropping systems (Kim and Dale, 2005). Crop residue removal, particularly at high rates, can be detrimental to the soil and environment in the long term through increased water erosion and nutrient loss (Wilhelm et al., 2004), but the addition of CCs is a potential ameliorative practice to reduce soil erosion and recycle nutrients, allowing sustainable removal of residues (Fronning et al., 2008).

The potential of CCs for offsetting C and nutrient losses after residue removal depends on CC biomass yield, CC species, soil type, and management. Studies specifically assessing crop residue removal vs. CC interactions are few. In Michigan, Fronning et al. (2008) reported that a rye CC did not increase the soil C pool over non-CC plots after 3 yr in a corn–soybean rotation when crop residues was removed for off-farm uses. In eastern South Dakota, Stetson et al. (2012) reported that the addition of wheatgrass (*Agropyron caninum* L.) and lentil CCs to a corn–soybean rotation after corn stover removal had no significant effects on soil organic C concentration compared with plots without CCs after 8 yr, but the soil C tended to decline when stover was removed at high rates and no CCs were added. In south-central Nebraska, the addition of a winter rye CC and animal manure following corn stover removal from irrigated no-till continuous corn did not reduce the susceptibility to wind erosion but offset the negative effects of stover removal on near-surface soil aggregate stability and soil organic C after 3 yr (Blanco-Canqui et al., 2014).

In some cases, CCs can also be harvested for biofuel if sufficient biomass is produced and enough is left to still protect the soil and maintain soil properties and productivity (Baker and Griffis, 2009). Across eight locations in the US Midwest, Baker and Griffis (2009) estimated that 1 to 8 Mg ha^{-1} yr^{-1} of winter rye CC biomass can be produced in corn–soybean rotations. It is important to consider that CCs require irrigation and fertilization similar to primary crops to achieve high biomass yields. Across 30 locations in the United States, Feyereisen et al. (2013), using a simulation model, estimated that winter rye, as a potential CC species, can produce about 4.2 Mg ha^{-1} of biomass. The same study suggested that winter rye could be grown on 7.44 × 10^{6} ha under continuous corn and 31.7 × 10^{6} ha under a corn–soybean rotation in the United States. Producing cellulosic biomass from CCs can also reduce NO_3 leaching relative to biomass- or grain-based feedstock for biofuel from primary crops (Syswerda et al., 2012).

The literature reviewed suggests that CCs can be a component of a myriad of possibilities to produce biomass for biofuel while enhancing soil ecosystem services. Cover crops can reduce the adverse effects of crop residue removal on soil properties and can also be harvested as biofuel feedstock. Cover crops can also support the establishment of energy crops by serving as a "nurse" crop (Heaton et al., 2014). These potential multiple uses of CCs require further investigation.

ARE COVER CROPS MULTIFUNCTIONAL?

Our review indicates that CCs can provide numerous ecosystem services including control of water and wind erosion, improvement in soil physical, chemical, and biological properties, sequestration of soil organic C, nutrient cycling, suppression of weeds, improvement in wildlife habitat and diversity, potential provision of both forage for livestock and feedstock for cellulosic biofuel production, and increased crop yields in regions with abundant precipitation (Fig. 5). Figure 5 provides further details about the ecosystem services that the appropriate and successful use of CCs can provide. Some of the ecosystem services from CCs, such as improvement of soil physical properties (i.e., aggregate stability, water infiltration, bulk density, temperature fluctuations) and biological properties (i.e., microbial community, earthworm population) as well as soil C sequestration are not sometimes realized, yet these soil properties are important to long-term agricultural productivity and environmental quality.

Cover crops provide many ecosystem services, but not all the ancillary benefits are measurable immediately. For example, while CCs do not always result in immediate increases in subsequent crop yields, the establishment of CCs provides vegetative cover and

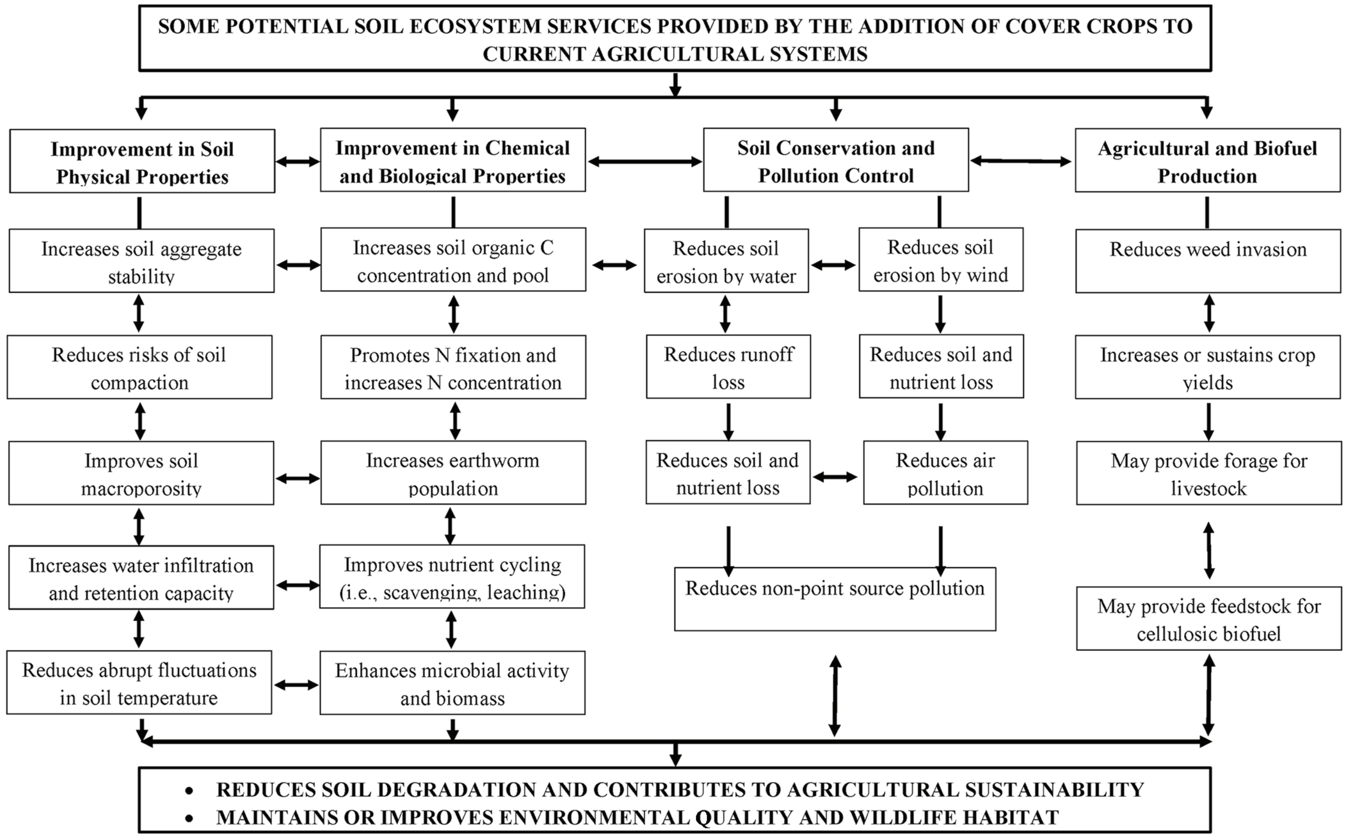


Fig. 5. Cover crops are multifunctional and could provide potential interrelated benefits. The arrows pointing in both directions indicate mutual relationships and interactions among parameters.

thus reduces wind and water erosion and improves soil physical, chemical, and biological processes (Blanco-Canqui et al., 2013a). Also, by adding root biomass, CCs can increase soil organic C concentrations and enhance microbial activity, which in turn can improve soil aggregation, aeration, water infiltration, porosity, and other soil physical processes and properties (Blanco-Canqui et al., 2011). All these CC-induced improvements in soil processes are essential to sustainable agricultural production and environmental quality and deserve consideration.

When combined with improved management systems such as no-till, CCs can enhance and increase the magnitude of benefits of current no-till and reduced-tillage practices relative to these same tillage systems without CCs (Blanco-Canqui et al., 2011). Mixtures of CCs can be more multifunctional than a single species because each plant species performs different and specific functions in the soil. For example, mixing radish with rye can alleviate both soil compaction and soil erosion risks due to the bio-drilling potential of radish and abundant aboveground biomass cover produced by rye (Chen and Weil, 2010).

The ecosystem services provided by CCs are not independent but rather are all strongly interrelated (Fig. 5). A given benefit contributes to the next benefit. For example, the accumulation of soil organic C with time under CCs contributes to improved soil properties such as soil aggregate stability and macroporosity, which can concomitantly result in increased water infiltration and reduced risks of water erosion Also, enhanced aggregate formation and stability not only reduces water and wind erosion but also promotes C and nutrient protection, storage, and cycling. Similarly, an increase in soil organic C concentration, improvement in soil aggregation, and reduction in soil bulk density with CCs can also reduce a soil's susceptibility to compaction in the long term (Blanco-Canqui et al., 2013b). Interactions among soil physical, chemical, and biological properties directly affect soil and water conservation, soil fertility, agricultural production, and environmental quality (Fig. 5).

Comprehensive studies quantifying all ecosystem services are needed to further our understanding of the multi-functionality of CCs. Recently, Schipanski et al. (2014) reported that CCs increased eight (biomass production, N supply, soil C storage, NO_3 retention, erosion control, weed suppression, arbuscular mycorrhizal fungi colonization, and beneficial insect conservation) of 11 ecosystem services without reducing subsequent crop yields, but the CCs had no effect on insect pest suppression and N_2O reduction in a 3-yr soybean–wheat–corn rotation in the eastern United States. Characterization of soil processes and their complexities at different temporal and spatial scales after CC inclusion is needed to quantify the ecosystem services from CCs.

The use of CCs represents an opportunity to intensify annual cropping systems and to improve ecosystem services without dramatically altering current management practices (Fig. 5). Improving and increasing the essential services from agroecosystems to address food security, energy security, environmental quality, and overall agricultural sustainability are a priority. Cover crops have the potential to contribute to enhancement of the multi-functionality of agroecosystems to meet these challenges . For example, CCs can sustain or increase crop yields and provide forage for livestock and biomass for biofuel production without negatively affecting the ecosystem services that they provide. Selection of CC species, long-term management of CCs, and, most importantly, consideration of site performance and the challenges of CCs will be necessary to achieve the multi-functionality of CCs.

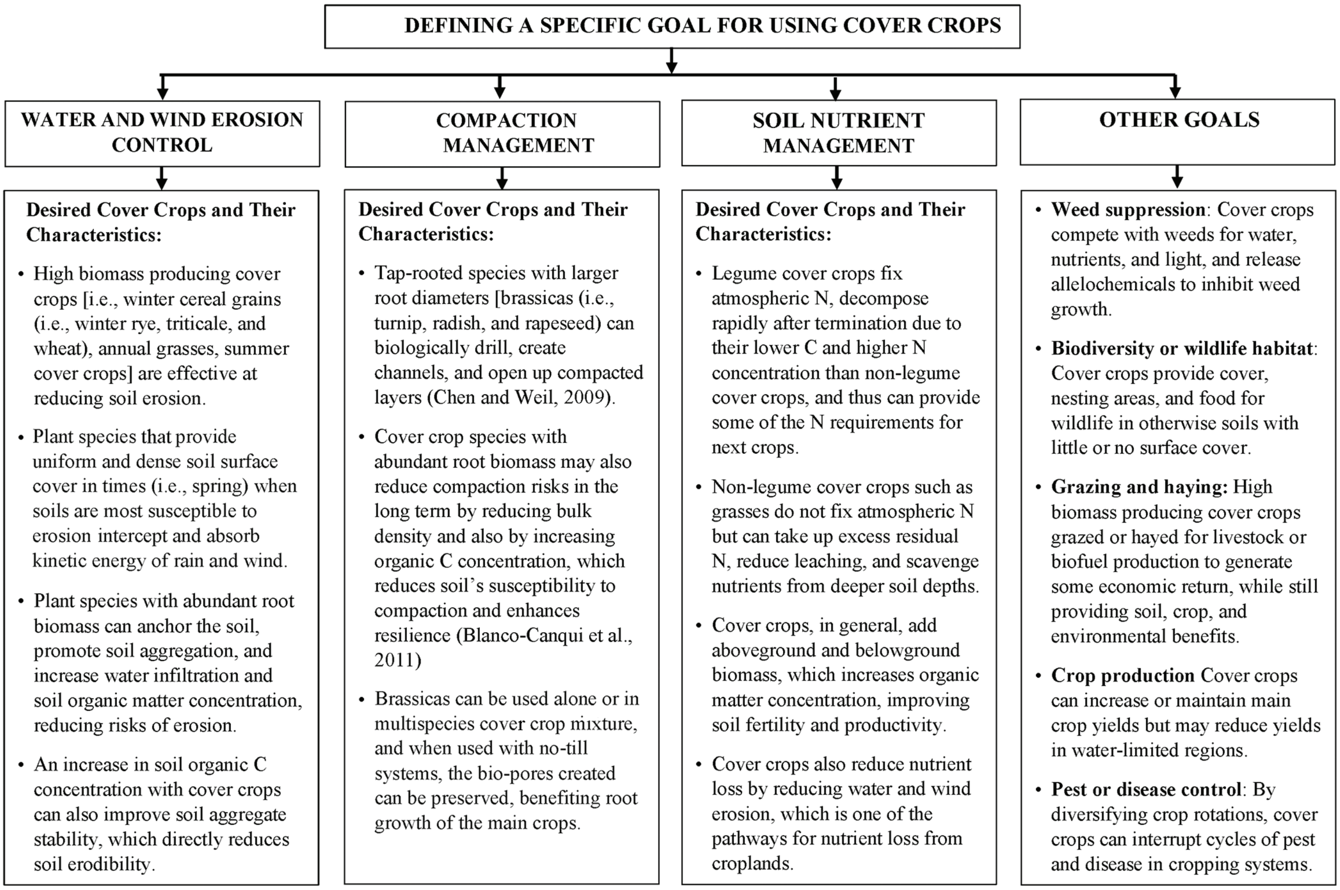
SITE SPECIFICITY AND CHALLENGES OF PREDICTING COVER CROP PERFORMANCE

While our review highlights the positive effects of CCs on a number of interrelated ecosystem services, it is important to recognize, as noted throughout this review, that CC effects on soil and crop production are complex and site specific. Local factors such as precipitation (amount, intensity, and frequency), potential evapotranspiration, soil type, cropping and tillage system, and site-specific management (i.e., selection of CC species, CC planting and termination dates and methods) and their interactions impact the performance and effects of CCs.

For example, as discussed above, differences in precipitation among regions can dictate the viability and performance of CCs. There will be trade-offs between soil ecosystem services provided by a CC and CC establishment and management costs. For example, while CCs reduce soil erosion, reduce N leaching, increase soil organic C, and provide other benefits, CC production costs (labor, seed and planting costs, water use, and others) must be balanced with the soil benefits that CCs provide. Cover cropping can be a more viable alternative if inorganic fertilizer costs continue to increase and some government cost-share programs are available.

Identification of the goal for cover cropping is key for their adoption and management. The goal will dictate the choice of CC species, planting date, seeding rate, termination date, and other management options. Identification of the goal for CCs can influence the success for each location and site-specific operation. The goals can include: (i) management of wind or water erosion, (ii) improvement in soil fertility and productivity, (iii) management of soil compaction, (iv) production of forage for grazing or haying, and (v) others (Fig. 6). For example, taprooted CCs such as brassicas (i.e., radish, turnip) alone or mixed with other species can be used for managing soil compaction (Cresswell and Kirkegaard, 1995; Chen and Weil, 2010), non-legumes or grass CCs for reducing N leaching (Rasse et al., 2000; Kaspar et al., 2012; Quemada et al., 2013), legume species for improving soil fertility (Mansoer et al., 1997; Wang et al., 2009; Blanco-Canqui et al., 2011), and high-biomass-producing CCs for controlling soil erosion and increasing soil organic C stocks (Kaspar et al., 2001; Blanco-Canqui et al., 2013a).

If multiple goals are pursued simultaneously, growing a multispecies mixture of CCs can be a potential strategy to obtain multiple benefits relative to growing a single species alone (Tosti et al., 2014). Because no single CC species can provide all possible ecosystem services, a combination of plant species could deliver additional benefits. Mixing CC species can balance the C/N ratio, growth rate, canopy cover, and root growth pattern, optimize weed control, sequester C as well as N, increase biomass inputs, and most importantly, enhance diversity and wildlife habitat compared with single CC species. For example, legumes can fix and supply N to the next crop, while brassicas can alleviate the risks of soil compaction in legume–brassica



DEFINING A SPECIFIC GOAL FOR USING COVER CROPS

WATER AND WIND EROSION CONTROL

Desired Cover Crops and Their Characteristics:

- High biomass producing cover crops [i.e., winter cereal grains (i.e., winter rye, triticale, and wheat), annual grasses, summer cover crops] are effective at reducing soil erosion.
- Plant species that provide uniform and dense soil surface cover in times (i.e., spring) when soils are most susceptible to erosion intercept and absorb kinetic energy of rain and wind.
- Plant species with abundant root biomass can anchor the soil, promote soil aggregation, and increase water infiltration and soil organic matter concentration, reducing risks of erosion.
- An increase in soil organic C concentration with cover crops can also improve soil aggregate stability, which directly reduces soil erodibility.

COMPACTION MANAGEMENT

Desired Cover Crops and Their Characteristics:

- Tap-rooted species with larger root diameters [brassicas (i.e., turnip, radish, and rapeseed) can biologically drill, create channels, and open up compacted layers (Chen and Weil, 2009).
- Cover crop species with abundant root biomass may also reduce compaction risks in the long term by reducing bulk density and also by increasing organic C concentration, which reduces soil's susceptibility to compaction and enhances resilience (Blanco-Canqui et al., 2011)
- Brassicas can be used alone or in multispecies cover crop mixture, and when used with no-till systems, the bio-pores created can be preserved, benefiting root growth of the main crops.

SOIL NUTRIENT MANAGEMENT

Desired Cover Crops and Their Characteristics:

- Legume cover crops fix atmospheric N, decompose rapidly after termination due to their lower C and higher N concentration than non-legume cover crops, and thus can provide some of the N requirements for next crops.
- Non-legume cover crops such as grasses do not fix atmospheric N but can take up excess residual N, reduce leaching, and scavenge nutrients from deeper soil depths.
- Cover crops, in general, add aboveground and belowground biomass, which increases organic matter concentration, improving soil fertility and productivity.
- Cover crops also reduce nutrient loss by reducing water and wind erosion, which is one of the pathways for nutrient loss from croplands.

OTHER GOALS

- **Weed suppression**: Cover crops compete with weeds for water, nutrients, and light, and release allelochemicals to inhibit weed growth.
- **Biodiversity or wildlife habitat**: Cover crops provide cover, nesting areas, and food for wildlife in otherwise soils with little or no surface cover.
- **Grazing and haying:** High biomass producing cover crops grazed or hayed for livestock or biofuel production to generate some economic return, while still providing soil, crop, and environmental benefits.
- **Crop production** Cover crops can increase or maintain main crop yields but may reduce yields in water-limited regions.
- **Pest or disease control**: By diversifying crop rotations, cover crops can interrupt cycles of pest and disease in cropping systems.

Fig. 6. Goals of cover crop management and some desired characteristics of cover crops to achieve those goals.

CC mixtures. In grass–legume mixtures, grasses grow more rapidly than legumes, protect the soil from erosion, and promote weed control, while legumes sequester N that can be used by the companion grass or the subsequent crop. Mixing CCs can merge benefits from the several component crops and take advantage of the interactions among species for achieving multi-functionality (Kramberger et al., 2014; Tosti et al., 2014). Wortman et al. (2012b), using land equivalent ratios, found that multi-species mixtures of legume and brassica CCs were more productive than the CCs grown as monocultures. Planting a mixture of CC species can also minimize the risks of failure and costs of labor and replanting. The trend is that, in the future, the use of diversified and multiple plant species such as CCs will be an essential component of production systems, where each plant species has its function and interacts with other species to deliver multiple ecosystem services.

In summary, while there appear to be potential benefits from using multiple-species CCs, there are also challenges associated with their management. Challenges include increased costs of CC seed and possibly the need for different planting equipment (i.e., different seed sizes and planting densities), planting time, and termination requirements, which can affect the economic returns from CCs. The increasing interest in using diverse CC mixtures warrants a more comprehensive study on how these mixtures affect overall agricultural sustainability and environmental quality. Flexibility, adjustment to conditions, and acceptance of potential failures can be an integral part of the challenges of CC management.

ECONOMICS OF USING COVER CROPS

Economic evaluations of CCs in relation to soil benefits are essentially nonexistent in the literature, emphasizing the importance of expanding work into this area. However, some economic evaluation has been reported in relation to monetary effects on overall farm economics, grazing returns, and N fertilizer inputs. Flower et al. (2012) reported that the inclusion of an oat CC in a cereal rotation reduced the 3-yr gross margin in the Mediterranean climate of southwestern Australia. They concluded that long-term assessment of the profitability of CCs is needed to better understand the economic implications. Grazing of CCs has the potential to offset the costs of establishment and generate some profit. In the southern Piedmont of the United States, Schomberg et al. (2014) found that monetary returns between cattle-grazed and ungrazed winter rye CCs in cotton (*Gossypium hirsutum* L.) ranged from –US$26 to US$355 and averaged US$81 ha^{-1}.

Cover crops can provide supplemental N and reduce inorganic fertilizer requirements. Frye et al. (1985) compared hairy vetch, big flower vetch, crimson clover, and rye CC residues with corn residues as an N source for no-till corn during a 5-yr period in the southern United States and found that hairy vetch combined with 100 kg ha^{-1} of fertilizer N provided the highest grain yields and economic returns. Ott and Hargrove (1989) reported that legume CCs increased both average corn yield and yield variance. They also noted that the greater yield variance from the use of legume CCs could increase economic risk. A combination of CCs with inorganic fertilization can be an alternative to increase crop yields because CCs alone may not supply sufficient N. Mallory et al. (1998) reported that 2-yr CC sequences in Wisconsin consisting of a short-season crop followed by a CC (companion-seeded red clover [*Trifolium pretense* L.], sequentially seeded hairy vetch, sequentially seeded oat, and fallow) in Year 1 and corn in Year 2 were not an economical alternative to N fertilizer when valued solely as an N source, offering little or no potential long-term benefits.

As with all topics discussed here, the effects of CCs on the economics of farm production appear to be variable and probably location specific. There is potential to offset CC costs if grazing is involved (Schomberg et al., 2014). However, the scant data also suggest that overall farm margins can decrease in the short term, and N fertility management and economics may or may not be affected positively by the integration of CCs in the system. Overall, little economic analysis exists on the re-emerging crop–livestock systems with the integration of CCs. This illustrates the need for more work in this area, as with several other topics as outlined next.

RESEARCH NEEDS

1. A more systematic and quantitative assessment of all ecosystem services provided by CCs is needed. Studies have often focused on a single or a few soil and crop parameters and not comprehensively on all soil attributes considered through an interdisciplinary approach. Systems-approach studies are needed to better understand the multi-functionality of CCs.
2. The implications of grazing or haying CCs on soil and crop production deserve further evaluation. Integrating CCs with crop–livestock systems necessitates a better understanding of the effects of the new scenarios of single and multi-species CC management on soil and crop production. Published studies assessing the effects of haying or grazing CCs are few (Franzluebbers and Stuedemann, 2008; Blanco-Canqui et al., 2013a). For example, it is essential to define the feed quality of different CC species for enhanced animal performance. Indices or information on forage quality (e.g., chemical composition of CC residue samples) should be developed for different CC species to assess digestibility and livestock performance (Coleman and Moore, 2003).
3. Published literature on CC economics is limited. Comprehensive economic valuations of CCs and ecosystem services are needed to better understand the economic trade-offs. For example, haying or grazing CCs can provide benefits in the short term and offset the costs of CC production, but their implications for soil ecosystem services need to be evaluated.
4. The potential of CCs for ameliorating the adverse effects of (i) crop residue removal (baling and grazing) and (ii) harvest of corn silage or seed corn on soil erosion; soil physical, chemical, and microbial properties; and C and nutrient levels needs further assessment under different management scenarios and residue removal rates (Fronning et al., 2008). Cover crops can have particular potential following the harvest of corn silage or seed corn because of the longer time for growth than following conventional corn grain harvest.
5. Most CC research has been conducted in soils with high organic matter content or in highly fertile soils. We submit that CCs have more potential for improving soil properties and restoring soil C in degraded or low-fertility soils than in highly fertile soils. The limited or no changes in soil properties observed in some soils following CC establishment can be

due to the use of CCs in highly fertile soils. Thus, more CC research in more marginal soils (e.g., sandy, erosion-prone, low-organic-matter soils) is needed to test this hypothesis.

6. Cover crop impacts can be measurable in the long term, warranting the execution of long-term studies (i.e., >5 yr) to fully discern the impacts of CCs on soil and crop production to capture the year-to-year variability of weather conditions. On-farm and long-term studies of CC management across a wide range of soil types, precipitation inputs, and evapotranspiration rates with different cropping systems are needed. Most studies have been conducted in small research plots, which often do not fully reflect on-farm operations or the use of field equipment.
7. More research is also needed on: (i) CC selection (i.e., single species and multi-species) for different agroecosystems and (ii) CC management practices including planting and termination dates, site-specific selection of CC species and mixtures, methods of planting (i.e., aerial seeding), harvesting or termination protocols, and others.
8. While there is considerable published research on the use of CCs for weed suppression, there is a need for more detailed information on how specific CC practices influence weed populations in specific systems as well as a broader look at how CCs are beneficial for weed suppression in general. Perhaps a meta-analysis of the existing literature to evaluate general trends in what cover cropping strategies work and do not work in a range of agroecosystems would provide guidance as to which specific questions need more thorough attention.
9. Some additional research should include further quantification of CC effects on: (i) subsequent long-term crop productivity and yield stability, (ii) nutrient dynamics and effective release for the primary crops, and (iii) water quality improvement at the watershed scale.

CONCLUSIONS

This review indicates that CCs are multifunctional and provide a number of ecosystem services such as reduction in water erosion, wind erosion, and soil compaction (i.e., bulk density and compactibility), improvement in soil structural properties (i.e., aggregate stability) and hydraulic properties (i.e., water infiltration), and increase in soil organic C, microbial activity, and nutrient cycling. Cover crops increase or have no effects on subsequent crop yields but reduce crop yields in water-limited regions. In general, the adverse effects on subsequent crop yields increase with a decrease in precipitation because CCs use water and can reduce available water for the primary crops. The few available studies indicate that grazing or haying CCs do not negatively affect the multi-functionality of cover crops, suggesting that CC biomass removal for livestock or biofuel production can be another ecosystem service of CCs. Inclusion of CCs after crop residue removal for livestock or biofuel or during fallow periods is a potential practice to maintain soil ecosystem services. Cover crops growing in the same land area can support and allow production of all essential commodities: food (increase or sustain crop yields), fiber, fuel (biofuel feedstock), and feed (forage for livestock production), while still maintaining or improving soil and environmental quality. The extent to which CCs provide multiple ecosystem services is highly site specific and depends on the climate (i.e., precipitation), CC species (i.e., single and mixtures), the length of time in the field, and the initial soil C level, among others. For example, in general, CCs can have small or no effects on soil physical properties and organic C in the short term (<3 yr). A more detailed economic analysis of the potential trade-offs between CC production costs and ecosystem services of CCs is needed. Overall, CCs can provide multiple ecosystem services, but more systems-approach-based studies are needed to characterize the performance and multi-functionality (food, fiber, and feed as well as soil and environmental implications) of CCs for different CC management scenarios, soil types, cropping systems, agro-eco-zones, and climatic conditions.

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