Received: 23 March 2020 | Accepted: 24 August 2020

DOI: 10.1002/agg2.20105

Agrosystems, Geosciences & Environment OPEN ACCESS

REVIEW AND INTERPRETATION

Improving soil physical properties through the use of cover crops: A review

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Abstract

Improving soil physical properties is important to soil conservation. Cover cropping can improve soil physical properties and organic matter content which can reduce soil loss, and thereby improve land productivity and environmental quality. In this article, the benefits of cover crops (CCs) for improving soil physical and hydraulic properties are reviewed as well as some soil conservation benefits that might accrue. The review indicates that CCs reduce soil bulk density by approximately 4%, increase macropores by approximately 33%, and increase water infiltration by as much as 629%, as compared to soil with no CCs. These improvements have been reported to lead to as much as 96% reduction in soil loss. Some current knowledge gaps in understanding how CCs can improve soil physical properties have been identified, including identifying which biomass, aboveground or belowground biomass, plays a greater role in organic C accumulation. Future research should focus on the interconnectedness of soil pores generated by CCs and the influence of CCs on heat transport parameters to further improve soil physical properties and associated benefits.

1 | INTRODUCTION

The growing global human population and increasing requirement for food necessitates increased agricultural food production that in turn puts many demands on the soil. This leads to the implementation of management practices geared more towards increased profitability than soil quality conservation and improvement. Increased demand on soil can lead to degradation of its physical properties and ultimately cause soil loss (Montgomery, 2007).

Soil erosion and degradation is a serious problem globally, especially in the less developed tropical and subtropical countries (Lal, 2001). For example, the land area affected by human-induced soil erosion between 1980 and 1990 in Africa, Asia, and South America have been estimated to be 494, 748, and 243 Mha, respectively (Oldeman, Hakkeling, & Sombroek, 1991). This leads to a decline in soil quality and productivity (Lal, 1997)

One way to reduce soil erosion and sustainably manage soil and its nutrients for increased productivity is through incorporation of cover crops (CCs) into crop rotation cycles (Dabney, Delgado, & Reeves, 2001). Cover crops are grown because of the numerous benefits they provide, including protecting the soil from wind and water erosion (Dabney et al., 2001). By covering the soil, both living CCs and their residues left on the soil can reduce evaporation, and help

Abbreviations: CCs, cover crops; NCCs, no cover crops.

conserve soil moisture. Cover crops can also reduce surface seal formation which increases water infiltration into the soil, and reduces runoff (Ruan, Ahuja, Green, & Benjamin, 2001) and enhance soil porosity through bio-pores formed by roots and increased earthworm activity (Lal, Regnier, Eckert, Edwards, & Hammond, 1991). Cover crops have been reported to benefit soil physical properties compared with no cover crops (NCCs) by lowering soil bulk density (Blanco-Canqui, Mikha, Presley, & Claassen, 2011; Haruna, Anderson, Nkongolo, & Zaibon, 2018a), improving soil organic carbon (SOC) and aggregation (Steenwerth & Belina, 2008), increasing the proportion of macropores (Cercioglu, Anderson, Udawatta, & Haruna, 2018), increasing water retention (Basche et al., 2016), saturated hydraulic conductivity (Yu et al., 2016), and water infiltration (Haruna, Nkongolo, Anderson, Eivazi, & Zaibon, 2018b), and reducing soil loss (Zhu, Gantzer, Anderson, Alberts, & Beuselinck, 1989).

Organic matter is lost through soil tillage (Hou et al., 2012). For example, the average annual organic carbon (OC) loss from the soil during a 15-yr period (from 1972 to 1995) from two moldboard plowed watersheds were 187 kg C ha^{-1} and 165 kg C ha^{-1} (Moorman, Cambardella, James, Karlen, & Kramer, 2004). Similarly, Koch and Stockfisch (2004) reported that tillage increased the redistribution and decomposition of OC which led to the rapid loss of SOC. During the slow decay of organic matter, humus, which is resistant to decomposition, is formed. Humus binds soil particles together and promotes soil aggregation and soil structure (Sollins, Homann, & Caldwell, 1996). Improved soil structure exerts important influences on the soil (Bronick & Lal, 2005).

Cover crops have been receiving attention from researchers and funding agencies and this has led to increased research on the benefits and adoption of CCs. For example, Kladivko et al. (2014) reported that the potential for CC adoption in 10 counties spread across Ohio, Indiana, Illinois, Iowa, and Minnesota ranged between 34 and 81%. This was attributed to more understanding of the role of CCs in improving soil health parameters. Perceived benefits are strongly associated with farmer and producer willingness to adopt CCs (Arbuckle & Roesch-McNally, 2015) and this can impact soil quality and productivity. However, our current knowledge on some of the processes that lead to CC benefits is still poor. Most studies are still inconclusive and have conflict with other studies. This review is intended to harmonize current results on the benefits of CCs in improving soil physical properties and soil conservation, while identifying certain gaps that need to be filled in the understanding of current cropping systems.

In this review, published papers on CCs and soil physical properties were collected. Results were summarized in tables, analyzed, and synthesized. A global search using the topic keywords was performed in Web of Science and Google Scholar to identify published studies of interest. The following sections discuss, first, soil physical properties and CCs, then, the influence of CCs on soil physical properties.

Core Ideas

- Cover crops improve the soil biopores and the saturated hydraulic conductivity of soils.
- Cover crops reduce soil density, increase water infiltration, and reduce runoff.
- Future research is needed to improve the current knowledge on cover crop usage.

2 | SOIL PHYSICAL PROPERTIES

Physical properties of the soil that determines its quality include, bulk density, porosity, and water retention. These properties, in turn, determine the water and nutrient-holding capacity of the soil. Soil physical properties also influence water and nutrient movement to rhizosphere and soil organisms activity.

Soil porosity is the most important soil physical attribute that influences water infiltration and movement. According to soil pore classification (Soil Science Society of America, 2008), macropores and micropores represent those pores that drain at <3 cm and between 3 and 300 cm water tension, respectively. This means that macropores and mesopores are responsible for drainage under gravity, while micropores are responsible for plant available water. Macropores are characterized by a large degree of pore continuity. However, the mesopore system has less pore continuity and higher tortuosity (Luxmoore, 1981; Messing & Jarvis, 1993).

Soil water represents a small portion of the water in the hydrologic cycle. However, the availability of soil water has a controlling influence on ecosystem processes at different scales (Western, Grayson, Bloschl, & Wilson, 2003). Soil water controls plant growth and influences a variety of soil processes including erosion, chemical exchange, microbial activity, transport of solutes and water, energy balance of the soil–plant system, and pedogenesis (Western et al., 2003). The relationship between water content and water potential partly determines these effects and can be used to determine soil's capacity to retain water.

Water retention is a hydro-physical property of soils that can be described by the relationship between soil water content and soil water potential (Walczak, Moreno, Sławiński, Fernandez, & Arrue, 2006). Two soils at equal matric potential may not always hold equal amounts of water, therefore they may differ in the amount of water available for plants. Agronomically, the important factor is the amount of water available to plants; or the amount of water between field capacity and wilting point. A common requirement is to know this relationship in non-saturated soil through the water characteristic curve. Normally, this curve represents the potential as a function of the volumetric water content of the soil, and, at other times, the volumetric water content of the soil as a function of the matric potential (Pérez-de-los-Reyes et al., 2011).

2.1 | Cover crops

Cover crops provide soil conservation benefits by providing protective vegetative cover during a fallow period or time between the harvest of a previous year's crop, and the planting of the following year's crop. Lu, Watkins, Teasdale, and Abdul-Baki (2000) referred to CC as any crop planted primarily to manage soil health, weeds, water quality, biodiversity, pests, and diseases. Most CCs are not grown solely for economic benefits, but for the ecosystem benefits they provide. As such, Yunusa and Newton (2003) referred to CCs as "primer plants" or crops grown to condition the soil for subsequent crops.

Growing CCs has been a popular practice in crop production throughout history (Reeves, 1994). Cover crops were originally grown as green manures, serving as a mulch and soil amendment, and were later incorporated into soil to improve fertility (Kasper & Singer, 2011). Utilizing green manures as a source of N was a standard practice in the United States until the mid-20th century, when synthetic N fertilizers became widely available (MacRae & Mehuys, 1985). Currently, the use of synthetic N fertilizers dominates grain crop production, limiting the use of green manure CCs.

Cover crops are able to fix atmospheric N, sequester C into the soil, and suppress weeds. Moller, Stinner, and Leithold (2008) estimated that leguminous CCs fix between 60–80 kg ha^{-1} of N into the soil compared with non-leguminous CCs. Non-leguminous CCs can also immobilize excess soil N, thereby reducing N loss. Fisk et al. (2001) reported that using an annual medic (*Medicago lupulina* L.) or a clover (*Trifolium* spp.) CC in no-till corn (*Zea mays* L.) reduced winter annual weeds by 41–81% compared with no cover crop (NCC). Cover crops can enhance soil quality through addition of organic matter when incorporated into the soil, helping to reduce compaction, increase infiltration, while reducing water and nutrient runoff, and reducing non-point source pollution. Wyland et al. (1996) reported a 65–70% reduction in nitrate leaching when CCs replaced winter fallow. Cover crops also reduce soil erosion from splash detachment by reducing the kinetic energy of raindrops (Haramoto & Gallandt, 2005).

A single CC cannot provide all these benefits. However, having a suite of CCs can provide the most benefits, both from an agronomic and environmental perspective. Some of the most common leguminous CCs used by producers and researchers include alfalfa (*Medicago sativa* L.), Austrian winter pea (*Pisum sativum* L. subsp. *arvense*), crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* Roth), sunn hemp (*Crotalaria juncea* L.) and subterranean clover (*Trifolium subterraneum* L.). Some of the most common grass cover crops include cereal rye (*Secale cereale* L.), oat (*Avena sativa* L.), annual ryegrass (*Lolium multiflorum* Lam.), and Sudan grass (*Sorghum* × *drummondi*). Others include the summer or cool-season annual broadleaf grain, buckwheat (*Fagopyrum esculentum* Moench) and brassicas (Teasdale et al., 2007). Below, the benefits of using CCs to improve soil physical properties are discussed and its implications on soil productivity and environmental sustainability.

2.2 | Cover crops and soil organic carbon

Soil organic C plays an important role for improved crop productivity and environmental sustainability. Within the soil ecosystem, OC has been reported to improve microbial activity and soil homogenization (Zhu, Hu, Wang, & Wu, 2019), water availability (Drenovsky, Vo, Graham, & Scow, 2004), nutrient availability (Weintraub, Scott-Denton, Schmidt, & Monson, 2007), and crop yield (Nkongolo & Haruna, 2015). Accumulation of SOC increases C sequestration and thus environmental sustainability (West & Marland, 2003). A detailed description of the importance of SOC to nutrient cycling, microbial activity, and CO_2 sequestration is beyond the scope of this paper. However, because of its importance in improving soil physical and hydraulic properties, the subsequent paragraphs discuss the influence of CCs on SOC accumulation.

Haruna, Anderson, Nkongolo, Reinbott, and Zaibon (2017) and Haruna (2019) reported a 26 and 36% greater SOC in CC plots compared with NCC plots as a result of the decomposition of belowground biomass in silt loam soil (Table 1). Similarly, Kuo, Sainju, and Jellum (1997); Sainju, Senwo, Nyakatawa, Tazisong, and Reddy (2008); Sainju, Singh, and Whitehead (2002); Villamil, Bollero, Darmody, Simmons, and Bullock (2006); and Blanco-Canqui et al. (2011) reported 7, 12, 9, 9, and 30% greater SOC, respectively, with the use of CCs compared with NCCs management. Comparably, Olsen, Ebelhar, and Lang (2014) reported CCs under no- tillage, chisel plow, and moldboard

TABLE 1 Cover crop (CC) influence on soil organic carbon (SOC) by location, soil texture, CC type, and soil depth

Location	Soil texture	Cover crops	Depth	Increase	Reference
			cm	%	
Missouri, USA	Silt loam	Cereal rye, hairy vetch, Austrian winter pea	0–30	26	Haruna et al., 2017
Tennessee, USA	Silt loam	Winter wheat	0–18	36	Haruna, 2019
Washington, USA	Silt loam	Cereal rye, Annual ryegrass	na	7	Kuo et al., 1997
Alabama, USA	Sandy loam	Cereal rye, hairy vetch, crimson clover	0–20	12	Sainju et al., 2002
Alabama, USA	Silt loam	Rye	0–20	9	Sainju et al., 2008
Illinois, USA	Silt loam	Hairy vetch, cereal rye.	0–30	9	Villamil et al., 2006
Kansas, USA	Silt loam	Sunn hemp	0–7.5	30	Blanco-Canqui et al., 2011
Illinois, USA	Silt loam	Hairy vetch, cereal rye	0–15	30	Olsen et al., 2014
			15–75	10	
			0–75	18	
Norway	Clay loam	Rye grass, crimson clover	0–25	ns	Yang et al., 2004
Iowa, USA	Loamy	Oat, cereal rye	0–10	ns	Kasper et al., 2006
California, USA	Loamy	Trios 102 merced rye	0–15	150–400	Steenwerth & Belina, 2008
Italy	Loamy	Durum wheat,	0–10	7	Mazzoncini et al., 2011
		sunflower	10–20	16	
			20–30	17	

Note. Some studies report differences in SOC at various depths. na, not available (authors did not report soil depth); ns, no significant differences.

plow improved SOC by 30, 10, and 18%, respectively, compared with NCCs under the same tillage managements in a silt loam soil. The outcomes of these studies indicated that, after 12 yr, CCs were effective in restoring SOC and sequestering back the SOC that was previously lost. Conversely, Yang, Singh, and Situla (2004) and Kasper et al. (2006) reported no significant difference in SOC between CC plots and NCC plots in clay loam and loam soils, respectively.

In a study by Steenwerth and Belina (2008) on a loam soil, plots with CCs had a 1.5- to 4-fold greater SOC compared with plots under NCCs after 6 yr of establishment. The higher SOC under CC management was attributed to the CC residue left on the soil surface. As such, it was concluded that CCs were more effective in adding SOC to soils than cultivation of cash crops alone. Similarly, Mazzoncini, Sapkota, Barberi, Antichi, and Risalti (2011) reported that both leguminous and non-leguminous CCs significantly increased SOC at the 0- to 30-cm depth of a loamy soil. However, unlike Mazzoncini et al. (2011), Steenwerth and Belina (2008) attributed the gains in SOC to the C returned to the soil as cash crop residues, aboveground CC biomass, and weeds. They concluded that the Mediterranean climate makes it easier to conserve or increase SOC.

In an earlier study on a silt loam soil by Kuo et al. (1997), the effects of CCs on SOC and soil carbohydrate concentration were variable because of a significant difference in total OC and carbohydrate produced by the CCs. It was reported that the aboveground biomass of the CCs decomposed rapidly within the soil (when buried in bags) with an average half-life of 43.1 ± 8.6 d. Furthermore, Liu, Ma, and Bomke (2005) reported that spring barley (*Hordeum vulgare* L.), cereal rye, and annual ryegrass CCs significantly increased the percentages of water-stable 2- to 6-mm aggregates after 2 and 8-wk incubation. It was concluded that CC effects on SOC and carbohydrates were because of the magnitude of C input from the different types of CCs used. This carbohydrate and polysaccharic fraction represent active soil-binding agents.

It is pertinent to point out that the quality and amount of biomass play a significant role in improving SOC (Ding et al., 2006; Haruna et al., 2017; Liu et al., 2005) and microbial biomass (Rankoth et al., 2019), and such benefits like reduction in bulk density can be obtained from SOC accrual (Haruna et al., 2018a). Another important factor for building up SOC is time. The introduction of CCs into the crop rotation cycle may trigger increased mineralization and CO_2 emissions at the early stages due to the increased microbial activity. Over time, microbial immobilization increases and, thus, an increase in SOC. As such, Sainju et al. (2002) suggested that SOC could be conserved and/or maintained by reducing SOC loss through mineralization and erosion.

A reoccurring theme in most literature on the influence of CCs on SOC accumulation is residue return and decomposition. These residues include aboveground and belowground biomass. Through microbial activity enhanced by improved gaseous interchange, available water, conducive soil temperature and pH, these residues are broken down and OC is added to the soil. What is missing in current literature is a quantification of which biomass, aboveground or belowground, plays a greater role in SOC accumulation. This information, if added to the current literature, can be used to improve the efforts on soil conservation practices while upgrading the state of knowledge on SOC dynamics within the soil. Furthermore, soil texture may play a role on SOC availability. This review suggests that clayey soils may reduce SOC availability compared with silt loam soil. However, more research is needed to determine the role of soil texture and CCs on SOC availability.

2.3 | Cover crops and soil density

As an indicator of soil compaction, soil bulk density is an important parameter of soil quality. It is influenced by natural/pedogenic processes such as texture, mineralogy, and soil depth. Other factors that influence bulk density include anthropogenic factors such as land and crop management. The inclusion of CCs into crop rotation cycles play a significant role on soil bulk density. Several mechanisms are responsible for the role of CCs on soil bulk density. On average, CC residues have less mass per unit volume as compared with soil minerals. As such, the more residues the soil contains, the lower the ratio of mass to volume. Further, the roots of living CCs penetrate the soil. The biopores left behind by plant roots increases soil porosity and this also reduces the mass/volume ratio of soils (Chaudhari, Ahire, Ahire, Chkravarty, & Maity, 2013).

Blanco-Canqui et al. (2011) studied the effects of CC in enhancing no-till potential for improving soil physical properties over 15 yr. The soil for this study was Geary silt loam (fine-silty, mixed, superactive, mesic Udic Argiustolls) with a <3% slope. The CC of choice was sunn hemp. Soil samples were taken at 0- to 7.5- and 7.5- to 15-cm depths. The result showed that CC had no effect on penetration resistance but affected bulk density. Cover crops affected bulk density at the 0- to 7.5-cm depth, with CC plots having 4% lower bulk density relative to NCC plots (Table 2). Villamil et al. (2006) reported that hairy vetch and winter rye CCs reduced bulk density and penetration resistance of the soil (silt loam) and therefore significantly increased total soil porosity at the soil surface compared to NCCs. Similarly, Demir, Tursun, and Isik (2018); Haruna (2019); Haruna and Nkongolo (2015a); Haruna et al. (2017); Nascente, Li, and Crusciol (2015); Sainju et al. (2002); and Adeli et al. (2020) reported that CC usage reduced soil bulk density by 7, 24, 3.5, 3, 14, 12, and 3%, respectively, compared with NCC usage. These authors concluded that CC roots and increases in SOC were responsible for the reduction in soil bulk density. Figure 1 illustrates the relationship between percent change in bulk density and percent change in SOC from data in Tables 1 and 2. It shows, on average, an inverse relationship between bulk density and SOC. This supports the conclusions by the aforementioned studies.

In a study on root penetration through compacted soils, Chen and Weil (2010) reported that forage radish (*Raphanus sativus* L. var. *longipinnatus* 'Daikon') could penetrate sandy loam soils and alleviate compaction at the 15- to 50-cm depth. Williams and Weil (2004) reported similar findings. Conversely, in an earlier study, Wagger and Denton (1989) reported that human and machinery traffic significantly increased soil bulk density while CCs had no effect on alleviating bulk density on a sandy loam. More recently, Cercioglu et al. (2018); Chan and Weil (2011); Garcia, Li, and Rosolem (2013); Haruna and Nkongolo (2015b); Jokela, Grabber, Karlen, Balser, and Palmquist (2009); Nouri, Lee, Yin, Tyler, and Saxton (2019); Sainju et al. (2008); Teixeira, Borges, Rogque, and Oliveira (2016); and Reichert, Pellegrini, and Rodrigues (2019) all reported no significant differences in soil bulk density between CC and NCC plots. The contrasts in these reports suggests that the benefits of CCs in alleviating soil compaction may require time (Haruna et al., 2018a). Growing CCs without a reduction in soil trafficking and possibly tillage may not yield the desired significant benefits in soil bulk density. Review of current literature shows more benefit of CCs on soil bulk density on clayey soils compared to silt loam soils. This suggests that soils that have a naturally lower density may benefit more from CCs.

2.4 | Cover crops and pore-size distribution

Cover crops can influence soil pore size distribution in various ways. Increased SOC increases soil aggregation and stability and this results in a more prolific root growth. For the purpose of this review, the discussion is focused on macropores (>500-μm radius), coarse mesopores (30- to 500-μm radius), fine mesopores (5- to 30-μm radius) and micropores (<5 μm radius) (Rachman, Anderson, Gantzer, & Alberts, 2004; Zaibon, Anderson, Kitchen, & Haruna, 2016). In a study by Haruna et al. (2018a) on a silt loam soil (Table 3), cereal rye CC improved the proportion of macropores by 30%, averaged over two depths (0–10 and 10–20 cm) 2 wk after CC termination and spring tillage (compared to NCC management), probably due to an increase in SOC and the activity of CC roots. This study suggested that the macropores generated by CC may persist for some time.

TABLE 2 Cover crop (CC) influence of soil bulk density by location, soil texture, CC type, and soil depth

Location	Soil texture	Cover crops	Depth	Decrease	Reference
			cm	%	
Kansas, USA	Silt loam	Sunn hemp	0–7.5	4	Blanco-Canqui et al., 2011
Illinois, USA	Silt loam	Rye	0–5	6	Villamil et al., 2006
		Rye or hairy vetch		7	
		Rye or hairy vetch-rye		7	
Alabama, USA	Sandy loam	Cereal rye, hairy vetch, crimson clover	0–20	7	Sainju et al., 2002
Brazil	Clay loam	Millet	0–5	24	Nascente et al., 2015
Missouri, USA	Silt loam	Cereal rye	0–10	3.5	Haruna & Nkongolo, 2015a
Missouri, USA	Silt loam	Cereal rye, hairy vetch, Austrian winter pea	0–30	3	Haruna et al., 2017
Turkey	Clay	Hairy vetch, buckwheat, Hungarian vetch, phacelia	0–20	14	Demir et al., 2018
Tennessee, USA	Silt loam	Winter wheat	0–6	12	Haruna, 2019
Mississippi, USA	Silt loam	Winter wheat	0–5	3	Adeli et al., 2020
Alabama, USA	Silt loam	Rye	0–10	ns	Sainju et al., 2008
Wisconsin, USA	Silt loam	Rye, Kura clover, red clover, Italian ryegrass	0–5	ns	Jokela et al., 2009
Maryland, USA	Sandy loam	Rye, forage radish, rapeseed	15–50	ns	Chen & Weil, 2011
Brazil	Clay	Millet, sunn hemp, sorghum–sudangrass	0–5	ns	Garcia et al., 2013
Missouri, USA	Silt loam	Cereal rye	0–20	ns	Haruna & Nkongolo, 2015b
Brazil	na	Millet, sunn hemp	0–10	ns	Teixeira et al., 2016
Missouri, USA	Silt loam	Cereal rye, hairy vetch, Austrian winter pea	0–20	ns	Cercioglu et al., 2018
Tennessee, USA	Silt loam	Hairy vetch, winter wheat	0–15	ns	Nouri et al., 2019
Brazil	Loam	Oat	0–6	ns	Reichert et al., 2019

Note. Some studies report differences in bulk density at various depths. ns, no significant differences.

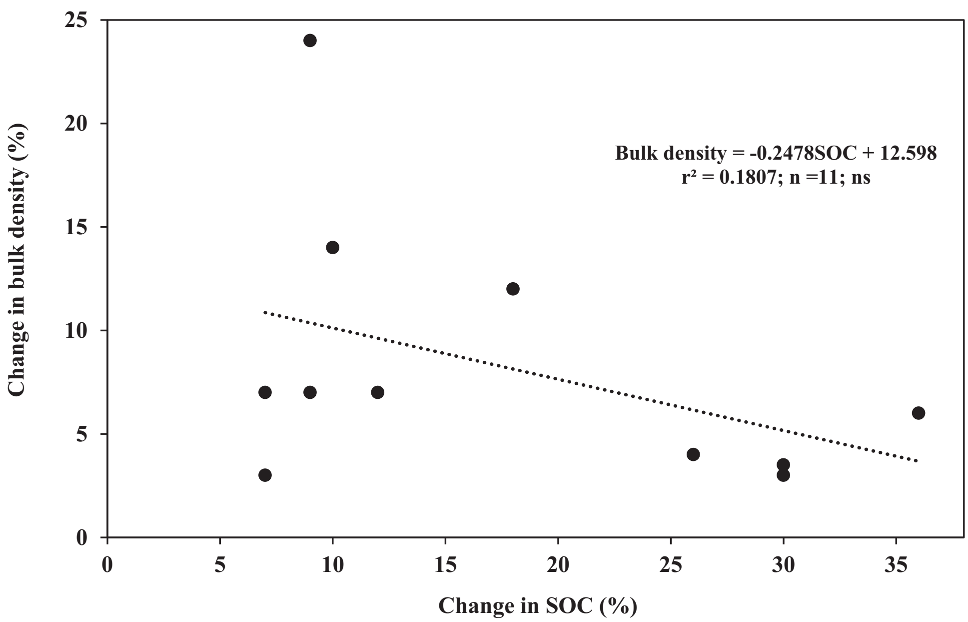

FIGURE 1 Relationship between percent change in bulk density and percent change in soil organic carbon (SOC) from studies in Tables 1 and 2

TABLE 3 Cover crop (CC) influence on pore size distribution by location, soil texture, CC type, and soil depth. Please note that pore size diameters used for the classification of pores into macropores, mesopores, and micropores varied among studies

Location	Soil texture	Cover crops	Depth	Macropores		Mesopores		Micropores		Reference
			cm	% increase	% decrease	% increase	% decrease	% increase	% decrease	
Missouri, USA	Silt loam	Cereal rye	0–20	30						Haruna et al., 2018a[a]
Illinois, USA	Silt loam	Rye	3–10	29		6				Villamil et al., 2006[b]
		Rye or hairy vetch		11		6				
		Rye or hairy vetch-rye		14		7				
France	Loam	Red fescue	0–10	67	–					Carof et al., 2007[c]
		Bird's-foot-trefoil		33	–					
		Alfalfa		50	–					
		Red fescue	10–20	–	67					
		Bird's-foot-trefoil		12	–					
		Alfalfa		–	60					
Brazil	Clay	Sorghum, sudangrass	0–5	2						Garcia et al., 2013[d]
		Pearl millet		2						
		Sunn hemp		1						
Missouri, USA	Silt loam	Cereal rye, hairy vetch, Austrian winter pea	0–10 and 10–20	33						Cercioglu et al., 2018[a]
Missouri, USA	Silt loam	Cereal rye	0–10	ns	ns	ns	ns	ns	ns	Haruna and Nkongolo, 2015b
Nebraska, USA	Silt loam	Cereal rye	0–10	ns	ns	ns	ns	ns	ns	Sindelar et al., 2019

Note. Note that some studies report differences in pore sizes at various depths. Other studies also reported differences in pore sizes due to specific CCs. ns = no significant differences.
[a]Macropore = >1,000 µm. [b]Macropore = >50 µm; Mesopores = 0.5–50 µm. [c]Macropores ≥ 1,767 µm. [d]No pore classification provided.

Similarly, Villamil et al. (2006) also reported that changes in pore-size distribution in a silt loam soil are reflected in significant increases in transmission (interconnected) pores with the use of CCs.

Table 3 shows the influence of CCs on pore size distribution by location, soil texture, CC type, and soil depth. Carof, De Tourdonnet, Coquet, Hallaire, and Roger-Estrade (2007) reported that CCs significantly improved macroporosity in a loam soil. Similarly, Garcia et al. (2013) reported that the use of CCs on a clayey soil increased macroporosity by 1–2% at the 0- to 5-cm depth due root activity. However, unlike in the study of Garcia et al. (2013), root morphology of CCs (leguminous vs. non-leguminous) did not significantly influence macroporosity and pore morphology and connectivity in the study of Carof et al. (2007). In a more recent study, Cercioglu et al. (2018) investigated the effects of CCs (cereal rye, hairy vetch, and Austrian winter pea) and biofuel crop management on computed tomography-measured pore parameters on a silt loam soil. It was observed that CC plots, on average, had about 33% more macropores than NCC plots on a 2,500-mm^2 area across all depths (0–10 and 10–20 cm). They further reported that CC plots had 50, 28, and 75% greater number of macropores than NCC plots, miscanthus (*Miscanthus* × *giganteus* J.M. Greef & Deuter ex Hodkinson & Renvoize), and switchgrass (*Panicum virgatum* L.), respectively. This suggests that CCs might provide similar benefits in improving pore size distribution as perennial crops (miscanthus and switchgrass).

Abdollahi, Munkholm, and Garbout (2014) studied the effects of CCs on pore characteristics of a sandy loam soil and reported that CCs increased air-filled macroporosity measured at −10 kPa and pore organization in soil compared with NCCs. It was concluded that CCs alleviated the effects of a tillage pan. A study conducted by Ess, Vaughan, and Perumpral (1998) on a loamy soil showed that cereal rye CC significantly reduced soil bulk density and increased noncapillary porosities compared to NCC at the 2.5- to 7.5-cm soil depth, even after multiple machine passes. It was suggested that soil compaction may have been alleviated by the reinforcing effect of a network of continuous roots within the soil. This suggests that CCs can improve soil quality.

Conversely, Haruna and Nkongolo (2015b) and Sindelar, Blanco-Canqui, Jin, and Ferguson (2019) reported that total porosity of silt loam soils did not change after 2 yr of including cereal rye CC into a crop rotation cycle. Further, CC might require more than 2 yr for establishment before their benefit on soil hydraulic properties can be observed.

Some of the conflicting reports on the influence of CCs on pore size distribution suggests that there are gaps in understanding the use of CCs for improving field hydrology. To bridge these gaps, both the morphology of CCs-generated pores, and the interconnectedness of these pores should be evaluated.

2.5 | Cover crops and soil water retention

Soil water retention curves are used for predicting water storage. The ability of the soil to retain water is dependent on soil porosity which can be impacted by management practices such as cover cropping. The biopores generated by CC roots can improve soil water retention. Cover crops have been reported to increase water retention at field capacity (Basche et al., 2016) (Table 4; Bilek, 2007; Hubbard, Strickland, & Phatak, 2013). As reported in Table 4, cereal rye CC on a silt loam and loamy soil significantly increased water retention at −10 and −30 kPa water pressures by 4 and 5%, respectively, compared with NCC management (Bilek, 2007). This range of water potentials usually corresponds to the presence of coarse mesopores (Kay, 1997), and thus suggests that the coarse mesopores generated by practicing cover cropping can increase water storage at these pressures. Further, Hubbard et al. (2013) reported an 18% increase in water retention at −30 kPa water pressures in CC plots compared with NCC plots on a loamy sand soil.

Similarly, Villamil et al. (2006) and Basche et al. (2016) reported that CCs increased plant available water content. Basche et al. (2016) showed that, at the 0- to 15-cm and 15- to 30-cm depths, CC management significantly increased plant available water content by 21 and 22%, respectively, relative to NCC management on a loamy soil. The increase in water retention at field capacity has been linked with an increase in soil organic matter (Emerson, 1995) and changes in soil aggregation (Guber, Pachepsky, Shein, & Rawls, 2004). Bilek (2007) and Villamil et al. (2006) both reported an increase in soil organic matter and aggregate stability due to CC management and this influenced water retention at field capacity, compared with NCC management.

Conversely, in a study on water balance with CCs and conservation agriculture in a Mediterranean climate, Ward, Flower, Cordingley, Weeks, and Micin (2012) reported no change in water storage due to CCs. In this study, CCs were found to have limited impact on total evaporation during the summer and fall periods. However, CCs had occasional short-term impacts on evaporation rate shortly after rainfall. The outcomes of these studies suggest that the inclusion of CCs in farming systems in regions with Mediterranean-type climate is unlikely to influence water balance, but may still increase overall sustainability of farming systems. Similarly, Blanco-Canqui et al. (2011), and Rorick and Kladivko (2017) reported no significant influence of CC management on soil water retention at field capacity and permanent wilting point. As such, CC

TABLE 4 Cover crop (CC) influence on soil water retention at −30 kPa (field capacity, FC), −1500 kPa (permanent wilting point, PWP) and available water by location, soil texture, CC type, and soil depth

Location	Soil texture	Cover crops	Depth	FC	PWP	Available water	Reference
			cm	% increase			
Maryland	Silt loam and loam	Cereal rye	0–7	5			Bilek, 2007
Georgia	Loamy sand	Sunn hemp	0–7.6	18	na	na	Hubbard et al., 2013
Iowa	Loam	Rye	0–15	13	ns	21	Basche et al., 2016
			15–30	ns	ns	22	
Illinois	Silt loam	Rye	3–10	ns	ns	4	Villamil et al., 2006
		Rye or hairy vetch				5	
		Rye or hairy vetch–rye				9	
Kansas	Silt loam	Sunn hemp	0–7.5	ns	ns	ns	Blanco-Canqui et al., 2011
Indiana	Silt loam	Rye	0–10	ns	ns	ns	Rorick & Kladivko, 2017

Note. Some studies report differences in soil water retention at various depths and for different CCs. na, not available; ns, no significant differences.

management did not improve plant available water content in these studies.

These contrasting results attest to an important underlying factor that should be considered when using CCs to improve soil physical properties: climate. The same influence of CCs in improving soil water storage in humid and subhumid regions may be responsible for possible drainage and increased evapotranspiration in semi-arid and arid environments.

2.6 | Cover crops and saturated hydraulic conductivity

The saturated hydraulic conductivity (K_{sat}) is a very sensitive measurement of water movement that varies temporally and spatially (Bodner, Scholl, Loiskandl, & Kaul, 2013) and is influenced by both pedogenic and anthropogenic factors. Parent material and soil texture are pedogenic factors that influence K_{sat}, while various land and crop management practices are examples of anthropogenic factors that influence K_{sat}.

Bodner, Loiskandl, Buchan, and Kaul (2008) conducted a study on natural and management-induced dynamics of K_{sat} along a cover-cropped field slope and reported that CCs (phacelia [*Phacelia tanacetifolia* Benth.], hairy vetch, rye, and mustard [*Brassica rapa* subsp. *oleifera*]) accounted for 9.7% of the total variability in near-saturated hydraulic conductivity. As such, they concluded that partial pore clogging by CC roots can negatively influence K_{sat}. On a silt loam soil in Arkansas, Keisling, Scott, Waddle, Williams, and Frans (1990) reported that a rye–hairy vetch CC sequence increased K_{sat} by 166% in the upper 5 cm of the soil, by 194% in the 5- to 10-cm depth and by 359% in the 10- to 15-cm depth compared with NCC treatment (Table 5). However, Wagger and Denton (1989) found no differences in soil porosity and K_{sat} when comparing a wheat (*Triticum aestivum* L.) and hairy vetch CC to fallow in a strip tillage system on a sandy loam soil.

Bodner et al. (2013) reported that management effects are often reflected in temporal variability of K_{sat}. However, despite an increase in pore heterogeneity, CC management neither had a significant main effect nor interaction effect on K_{sat}. Similarly, Yunusa and Newton (2003) compared the use of annual and perennial herbaceous and woody species as primer plants. These researchers concluded that annuals were not sufficiently effective in biopore formation to increase water conductivity. Further, Villamil et al. (2006) also reported no significant influence of CC management on K_{sat} in a silt loam soil. Conversely, Carof et al. (2007) reported a significantly higher hydraulic conductivity under CC management as compared to NCC management in a loamy soil and this was attributed to root

TABLE 5 Cover crop (CC) influence on saturated hydraulic conductivity (K_{sat}) by location, soil texture, CC type, and soil depth

Location	Soil texture	Cover crops	Depth	K_{sat}		Reference
			cm	% increase	% decrease	
Arkansas, USA	Silt	Rye, hairy vetch	0–5	166		Keisling et al., 1990
	loam		5–10	194		
			10–15	359		
North Carolina, USA	Sandy loam	Wheat, hairy vetch	2.5–10	ns	ns	Wagger & Denton, 1989
Austria	Loam to silt loam	Mustard, rye	na	ns	ns	Bodner et al., 2013.
Illinois, USA	Silt loam	Rye	3–10	ns	ns	Villamil et al., 2006.
France	Loam	Winter wheat, red fescue, bird's-foot-trefoil, alfalfa.	0–10	10		Carof et al., 2007.
Missouri, USA	Silt loam	Cereal rye	0–20	33		Haruna et al., 2018a.
Arkansas, USA	Silt loam	Rye-hairy vetch	0–15	126		Keisling et al., 1994.
Minnesota, USA	Silt loam	Rye	5–10	41		Liesch et al., 2011.
Ontario, Canada	Clay loam	Winter wheat	0–20	627		Drury et al., 2014.

Note. Some studies report differences in K_{sat} at various depths. na, not available (authors did not report soil depth); ns, no significant differences.

activity. Furthermore, root type did not significantly influence porosity and K_{sat}; there were no major differences between the grass CCs (fibrous-root type) and the leguminous CCs (tap-root type).

Integrating rye CC into corn production has been reported to significantly increase water permeability as a result of intense rye rooting (Liesch, Krueger, & Oschner, 2011). Similarly, Yu et al. (2016) reported that CC root-induced increases in hydraulic conductivity can reduce runoff from intense rainfall by up to 17% in a silt loam soil. Due to increased macroporosity generated by CC, Haruna et al. (2018a) reported that CC improved K_{sat} by about 32% as compared with NCC management, at 0- to 20-cm depth of a silt loam soil. Keisling, Scott, Waddle, Williams, and Frans (1994), Liesch et al. (2011), and Drury et al. (2014) reported 126, 41, and 627% increases, respectively, in K_{sat} under CC management as compared to NCC management. Increased hydraulic conductivity significantly benefits water infiltration into the vadoze zone.

2.7 | Cover crops and water infiltration

Adding winter CCs can increase water transpiration during the period when most fields are left bare. As a result, soil water infiltration can be increased. This is especially important in areas with very heavy spring precipitation (Haruna et al., 2018b). This leads to less runoff, a reduction in non-point source pollution, and consequently cleaner streams and rivers (Zhu et al., 1989).

Water infiltration is usually improved with an increase in macropores caused by CC roots. Cover crop residue left on the soil surface can improve water infiltration by reducing soil surface sealing and surface water runoff. Table 6 shows the influence of CCs on water infiltration rate and cumulative water infiltration by location, soil texture, and CC type. Kemper and Derpsch (1981) conducted an experiment on a clayey soil belonging to two different soil orders (Oxisols and Alfisols) in Brazil to investigate the influence of CCs (winter annual legume and rapeseed; *B. napus* L.) on infiltration. The results show that, compared to wheat stubble, the CCs improved infiltration rate by 416 and 629% on the Oxisols and Alfisols, respectively. They attributed this increase in infiltration rate to the bio-pores formed by the CC roots.

Similarly, Wilson, Lal, and Okigbo (1982) reported an increase in macropores and infiltration with the use of CCs on an eroded Alfisol in southern Nigeria. McVay, Radcliffe, and Hargrove (1989) measured infiltration rate on a coastal plain soil in Georgia using a sprinkler infiltrometer after 3 yr of cropping. Results show that the infiltration rate in no-till grain sorghum [*Sorghum bicolor* (L.) Moench] planted after hairy vetch CC averaged about 5.8 cm h^{-1}. Following a wheat CC, infiltration rate was about 4.2 cm h^{-1}, and following a winter fallow, infiltration rate was 3.8 cm h^{-1}. Bruce, Langdale, West, and Miller (1992), and Chalise et al. (2018) reported that the use of CCs increased infiltration rate by 100 and 79%, respectively, compared with NCCs. Furthermore, Folorunso, Rolston, Prichard, and Loui (1992) reported improved rainfall infiltration in CC plots compared with a fallow rotation. Haruna et al. (2018b) also reported improved water infiltration parameters in CC (cereal rye) on a silt loam soil compared with NCC management in a rain-fed system. All of

TABLE 6 Cover crop (CC) influence on water infiltration rate and cumulative water infiltration by location, soil texture, and CC type

Location	Soil texture	Cover crops	Infiltration rate	Cumulative infiltration	Reference
			——% increase——		
Brazil	Clayey	Rapeseed	416 and 629		Kemper & Derpsch, 1981.
Nigeria	Clay loam	Stylo	13		Wilson et al., 1982
Georgia, USA	Clay loam	Winter wheat	11		McVay et al., 1989
Georgia, USA	Clayey	Crimson clover	100		Bruce et al., 1992
South Dakota, USA	Silt loam	Rye–hairy vetch	79		Chalise et al., 2018
California, USA	na	Bromegrass		97	Folorunso et al., 1992.
		Strawberry clover		91	
Missouri, USA	Silt loam	Cereal rye		170	Haruna et al., 2018b
Kansas, USA	Silt loam	Sunn hemp		163	Blanco-Canqui et al., 2011
Maryland, USA	Silt loam and loam	Rye		83	Bilek, 2007
Tennessee,	Silt loam	Vetch		86	Nouri et al., 2019
USA		Wheat		116	

Note. Some studies report differences in cumulative infiltration for different CCs.

these demonstrate the ability of CCs to improve water infiltration into the soil.

Blanco-Canqui et al. (2011) reported that sunn hemp increased water infiltration rates and cumulative infiltration by three times relative to NCC plots on a silt loam soil. The increase in water infiltration was attributed to high earthworm populations enhanced by no-till and CC. Bilek (2007) reported that infiltration rate, cumulative infiltration, and hydraulic conductivity were significantly greater under CC management compared with NCC management on a silt loam soil. Similarly, Nouri et al. (2019) reported that under no-till management practice, the use of vetch and wheat CCs improved cumulative infiltration by 86 and 116%, respectively, compared with NCCs on a silt loam soil. This improvement in cumulative infiltration was attributed to higher porosity generated by the roots of the CCs.

Haruna et al. (2018b) reported that CC management resulted in a significantly higher sorptivity parameter as compared with NCC management. The outcome of this study suggested that the ability of CCs to reduce near-surface soil water content through transpiration could be important in very wet early growing seasons and thus CCs may lengthen the growing season of the cash crop by enabling farmers to plant earlier during wet springs. However, this same phenomenon can be detrimental in semiarid and arid regions and during drier growing seasons in humid and subhumid regions. Still, Daigh et al. (2014) contended that the differences in soil water content between CC and NCC management may not be significant enough to reduce crop productivity. Sims (1989) and Gardner (1992) suggested that, despite the near-surface soil water transpiration by CCs, cash crop yield could be maintained or improved through appropriate species selection and proper timing of CC termination.

2.8 | Cover crops and heat transport

Heat transport through the vadoze zone is an important soil physical property that influences water and nutrient transport, microbial activity, and crop productivity. With the current variability in global climate, heat transport is bound to become an important factor that influences crop productivity. Heat transport can be estimated based on thermal conductivity (λ), volume-specific heat capacity (C_V), and thermal diffusivity (D) (Hopmans, Simunek, & Bistrow, 2002).

Management practices that compact the soil have been reported to increase λ because the λ of soil minerals is greater than that of air and water (Bristow, 2002; Wierenga, Nielsen, Horton, & Kies, 1982). Furthermore, studies have reported a strong positive correlation between both SOC and water content and C_V (Adhikari, Udawatta, & Anderson, 2014; Haruna, 2019).

A study on the influence of perennial biofuel and CC management on soil thermal properties of an Alfisol in central Missouri showed that CCs (hairy vetch, cereal rye, and Austrian winter pea) had 13%, and 16% higher C_V at saturation and −33 kPa soil water pressure, respectively, compared with NCC (Haruna et al., 2017) (Table 7). The increases in C_V at saturation were attributed to a greater water content at those matric potentials and SOC in CC compared with NCC management. It was concluded that under laboratory-controlled conditions, CCs can help the soil buffer against extreme heat change. However, there

TABLE 7 Cover crop (CC) influence on soil thermal conductivity (λ), volumetric heat capacity (C_V), and thermal diffusivity (D) by location, soil texture, CC type, and soil depth

Location	Soil texture	Cover crop	Depth	λ	C_V	D	Reference
			cm	———	% difference	———	
Missouri, USA	Silt loam	Rye–hairy vetch–Austrian winter pea	0–10	ns	+19	−21	Haruna et al., 2017
Tennessee, USA	Silt loam	Winter wheat	0–6	ns	+28	−43	Haruna, 2019
Nebraska, USA	Silt loam	Rye	0–5	ns	ns	ns	Sindelar et al., 2019

Note. +, cover crops increased soil thermal property; −, cover crops reduced soil thermal properties. ns, not significant.

were no significant differences observed in λ between CC and NCC plots despite CCs having lower bulk density (Haruna, 2019; Haruna et al., 2017). Conversely, Sindelar et al. (2019) reported that CCs did not significantly influence thermal properties of a silt loam soil. This was probably because CCs had no significant effect on soil water content, bulk density, and SOC. However, thermal properties were more correlated with bulk density and water content than with SOC.

Currently, there are few studies evaluating the influence of CCs on these important heat transport parameters. More studies are needed to evaluate the possibilities and benefits of using CCs to buffer against extreme soil heat change in a changing global climate. Additionally, all current studies on the influence of CCs on soil thermal properties have been conducted on silt loam soils. Research is needed to improve understanding on how CCs impact soil thermal properties on other soil textural classes.

2.9 | Impacts of cover crops on soil conservation, water quality, and socioeconomic aspects of crop production

Soil loss can occur naturally, and it can be accelerated by human activity. Usually, the rate of natural soil loss approximately equals the rate of geologic soil formation (Montgomery, 2007). In this instance (where soil formation equals soil loss), soil loss is usually not an issue unless considering the loss of nutrients. Most annual soil loss occurs from a few intense events (precipitation or windstorm) and can be exaggerated on bare soils.

The leaves of living CCs and the residues left on the soil surface can provide a barrier between the soil and the kinetic energy of raindrops. As a result, soil aggregate integrity can be protected. Also, CCs slow down wind speeds at ground level and decreases the velocity of water in runoff thus reducing wind and water erosion. The presence of winter CCs has proven to be effective in reducing soil erosion. A study by Zhu et al. (1989) on an Udollic Ochraqualf in Missouri compared no-till soybean [*Glycine max* (L.) Merr.] plots seeded to CCs with a control treatment of NCCs. Mean annual soil losses from chickweed (*Stellaria media* L.), Canada bluegrass (*Poa compressa* L.), and downy brome (*Bromus tectorum* L.) CC treatments were decreased by 87, 95, and 96%, respectively, compared with the control plot. Bilbro (1990) conducted a study on an Amarillo silt loam soil (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs) on the impact of CCs on wind erosion in semiarid regions. The results showed that forage sorghum in 12.7-cm rows were effective in reducing wind erosion to below the tolerable rate of soil erosion at 11 Mg ha^{-1} yr^{-1}.

Cover crops can reduce soil loss from intense rainfall events in two ways, as a living canopy and as mulch (Dabney et al., 2001). The canopy protection of CCs depends on the type, quality, and stand of the crops used and may vary from season to season (Haramoto & Gallandt, 2005). The effectiveness of the mulch also depends on the quality and quantity of residues left on the soil surface (Erenstein, 2003). Therefore, the effectiveness of CCs in erosion reduction not only depends on the type and quality of the CCs, but also the season when they are grown. This higher surface cover can reduce soil loss and improve agricultural sustainability.

In a study on the influence of winter CCs on soil surface strength and infiltration rate, Folorunso et al. (1992) reported that bromegrass (*Bromus* spp.) and strawberry clover [*Trifolium fragiferum* L. ssp. *Bonanni* (C. Presl) Sojak.] CCs reduced surface soil strength by 38–41% relative to NCC. Consequently, steady infiltration rate and cumulative water infiltration increased by 37–41% and 20–101%, respectively, compared to NCC. As a result of increased infiltration rate, Adler et al. (2020) reported that cereal rye CC is an effective tool for reducing soil and nutrient loss in a no-till tile-terrace field. As such, Aryal et al. (2018) suggested the usage of CCs to reduce soil loss and winter nutrient loading into streams and rivers.

In a review of CC and soil quality interactions in agroecosystems, Reicosky and Forcella (1998) discussed the role of CCs in preventing wind and water erosion and C input to enhance soil quality. It was reported that C input from CCs can ensure long-term economic benefits with minimal impact on soil, water, and air quality because the SOC can improve water infiltration and storage, temperature, aeration, and soil structure (Hartwig & Ammon, 2002; Mirsky et al., 2012). Furthermore, Dumanski, Peiretti, Benites, McGarry, and Pieri (2006) suggested that select CCs can provide allelopathic benefits which can improve soil aggregation and promote a healthy soil by reducing requirements for pesticides and herbicides and control off-site pollution.

Shipley, Messinger, and Decker (1990) studied the ability of winter cover crops (hairy vetch, crimson clover, cereal rye, and annual ryegrass) to assimilate residual N fertilizer and thereby reduce N losses. After 336 kg N ha^{-1}, the average N uptake in mid-April was 48 kg N ha^{-1} for cereal rye, 29 kg N ha^{-1} for annual rye, 9 kg N ha^{-1} for hairy vetch, and 8 kg N ha^{-1} for crimson clover. Based on the percent recoveries of fall N in the aboveground dry matter, it was concluded that CCs recovered more fall N compared to native weed fallow and this can improve water quality. Similarly, in a decade-long study, Delgado, Dillon, Sparks, and Essah (2007) reported that CCs (winter wheat and cereal rye) scavenged an average of 200 kg N ha^{-1} when grown in vegetable potato (*Solanum tuberosum* L.) systems with high residual soil NO_3–N. Furthermore, these CCs were credited with recovering NO_3–N from underground water resources through their root systems.

Haruna and Nkongolo (2020) studied the influence of cereal rye CC on nutrient availability. It was reported that, after 3 yr, P availability was 14% greater in plots managed with CC compared with NCC. Since P is mostly lost in particulate form, Haruna and Nkongolo (2020) attributed the greater P under CC management to the soil conservation benefits of CC. Similarly, Gomez, Guzman, Giraldez, and Fereres (2009) reported that CC efficiently reduced runoff and sediment yield down to tolerable levels, resulting in 0.0333 kg m^{-2} yr^{-1} more available P as compared with NCC.

To this effect, Erenstein (2003) argued for CCs to be used as mulches to improve soil and water conservation, land preparation, and crop establishment should be done in a timely manner. For mulching to be socio-economically viable, it should be introduced through a transitional phase involving farmer learning, investments, local adaptation, and fine-tuning and institutional change. This will ensure farmer participation, community involvement and overall conservation of natural resources (Erenstein, 2003).

Like every practice, soil conservation faces obstacles. Some conservation practices are expensive to put in place and may not provide direct or immediate economic benefit to the producer. Since the major impact of soil erosion is felt downstream or close to streams, a land user may not be immediately willing to invest some capital to help "anonymous" persons (Troeh, Hobbs, & Donahue, 2004). Economics can also be a problem in many developing countries where agriculture is mostly subsistence and rainfed. Most farmers in developing countries may not have the capital required to implement conservation practices (Dumanski et al., 2006). In developed countries, producers are more willing to incorporate CCs into their cropping systems provided that it improves their economic advantage (DeLaune, Mubvumba, Fan, & Bevers, 2020). Hairy vetch has been reported to be consistently profitable in small grain rotations (Lu et al., 2000; Snapp et al., 2005). Furthermore, Larson, Roberts, Tyler, Duck, and Slinksy (1998) reported that hairy vetch CC improved corn yields across five N rates (0–224 kg ha^{-1}) compared to NCC at each application level. Average yield increases were 2.82 Mg ha^{-1} at 0 kg N and 0.50 Mg ha^{-1} at 168 kg N. Conversely, DeLaune et al. (2020) reported that, although Austrian winter pea, hairy vetch, crimson clover, and winter pea CCs did not significantly improve agronomic or economic advantage of cotton (*Gossypium hirsutum* L.), ecosystem services of CCs should be considered in cropping system decisions. Culture and tradition may also pose some challenges to soil conservation. Many direct land users are traditional in their approach and may be unwilling to stop practices used by previous generations which enhanced erosion like residue removal and tillage (Dumanski et al., 2006). As with human nature, the assurance of the comfort zone is more appealing than the challenge of change. Cover crops represent a choice for soil conservation.

The benefits discussed in this paper can only be realized when CCs have been well managed and fully established. Careful management of CCs include no-tillage, timely planting, and timely termination. For example, Munkholm, Richard, Heck, and Deen (2013) reported that poor soil structure from long-term (30 yr) moldboard plow reduced CC (oat and spring barley) efficiency in improving soil physical properties. Furthermore, Haruna et al. (2018a) reported that late planting significantly reduced CC (cereal rye) growth which reduced the hydraulic benefits of cereal rye CC. It was suggested that early planting (e.g., sowing the CC into standing cash crops) can improve CC benefits. Daigh et al. (2014) reported that timely termination of CCs can improve water conservation and improve cash crop productivity. Cover crops can also dry out soils and may reduce water content in dry years if not well managed (Dabney et al., 2001). Some might introduce new pathogens or pests to a field (Tillman et al., 2004). Good CC management may also take several years to fully establish (Noland et al., 2018). Therefore, careful planning is important to make CCs work.

3 | SUMMARY

The need to provide food and fiber for the growing global population has led to intensive agricultural practices that include converting forests and less capable lands to farmlands that require the use of intensive tillage and fertilizers. Intensive cultivation without the use of conservation methods causes soil erosion, degrades soil structure and the soil biotic community, leads to high sediment and nutrient loading in streams and is largely the cause of the hypoxic zones in many estuaries and oceanic gulfs around the world. They also lead to soil and nutrient loss from agricultural fields. Degraded soils reduce land productivity, thus requiring more land for food and fiber production.

In this article, previous and current literature on the use of CCs for improved soil physical properties and soil conservation and consequently improved land productivity, soil health, and environmental benefits were reviewed. The literature reported that soils with CCs had greater SOC, more macropores, better water retention, and reduced runoff from intensive rainfall. All these benefits to the soil can improve cropping systems and environmental sustainability.

Because including CCs in crop production requires additional labor and expenses, agricultural systems need to be honed to achieve both environmental (improved water retention, infiltration, reduced bulk density, soil and nutrient loss) and economic benefits for widespread use. To achieve improved systems, more federal and state support is needed to support the advance of knowledge on CC benefits, and to bridge current gaps highlighted in this review.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Haruna SI, Anderson SH, Udawatta RP, et al. Improving soil physical properties through the use of cover crops: A review. *Agrosyst Geosci Environ*. 2020;3:e20105. https://doi.org/10.1002/agg2.20105