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Review Paper

Critical review of the impact of cover crops on soil properties

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A B S T R A C T

Grasses as well as leguminous and non-leguminous broadleaves are the major categories of commonly grown cover crops worldwide. This review focuses on the contribution of cover crops to soil properties. The review first considers the single and mixed cover crops and shows that grass species are desirable for their decay and ability to provide substantial soil cover, broadleaf species are used for their quick decomposition and capacity of releasing residues into the soil, while the leguminous species are used for their ability to fix atmospheric nitrogen. Secondly, the impacts of cover crops on soil health are reviewed. Integrating cover crops into conventional cropping systems may reduce soil bulk density, improve soil structure and hydraulic properties to facilitate increased water infiltration and storage. Crop residue additions from cover crops may enhance soil organic C and N accretion as well as increase availability of P, K, Ca, Fe and Mg in some soil types under certain climatic conditions. Further, cover crops may provide a better condition for microbial activity, abundance, and diversity. Finally, the review shows that through proper management, cover crops may be utilized as an essential component of soil conservation practices for enhanced soil health. Still, further investigation is necessary to determine cover crop effects in additional cropping systems and climatic zones as well as the long-term effects of cover crops on soil properties, subsequent crop yield, and overall cropping system profitability. This review is an important source of information for crop growers, crop management institutions, universities, and crop consultants for sustainable agricultural production.

Contents

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1. Introduction

Cover crop management between cash crops is one of the oldest farming practices and is presently gaining attention worldwide (Romdhane et al., 2019). Cover crops may include any plant species grown for purposes beyond primary grain or forage production and are generally classified as leguminous broadleaves, non-leguminous broadleaves, or grasses. As defined by the Soil Science Society of America (SSSA), cover crops are those used to protect and improve the soil between times of regular annual crop production or between trees in orchards and vines in vineyards (Fageria et al., 2005).

At this time, several studies have demonstrated the utility of cover crops in agricultural production with many focusing upon either soil physical, chemical, or biological properties (Adetunji et al., 2020; Saleem et al., 2020). Indeed, Saleem et al. (2020) suggested that it is the additional root growth of cover crops that may provide benefits to soil including increases in soil organic carbon content, available nutrients, as well as soil aggregation. Additionally, cover crops have been found to enhance nutrient cycling, soil physicochemical and biological properties, as well as soil pest management and weed suppression. According to Sharma et al. (2018), cover crops contribute to reducing water evaporation from the soil thereby preserving soil moisture for the following crop. Though this has been observed in some environments (Basche et al., 2018), under water-limited conditions without irrigation, cover crops have frequently been found to limit soil moisture for subsequent crops (Nielsen et al., 2015, 2020).

Sustainable agriculture has been defined as the capability of production systems to produce uninterruptedly while avoiding negative effects on the environment (Tahat et al., 2020). Cover crops are an important component of sustainable agricultural development as they have been shown to improve soil health by enhancing the activity of microorganisms as well as their diversity and abundance. Cover crops may be an asset for sustainable agricultural development through several mechanisms including nutrient and water preservation, soil quality improvement, reduced soil erosion risk, as well as weed control (Teasdale & Daughtry, 1993), and soil pest management depending upon environmental factors (White et al., 2016). For example, cover crops increased the efficiency of applied N fertilizer in a Mediterranean climate (Gabriel et al., 2016). Beneficial predator insects may find habitat in cover crops (aboveground and residue) that may also act as non-host crops for pests in conventional crop rotations. According to Dabney et al. (2010), the addition of cover crops may be a significant source of organic matter to the soil that reduces soil erosion and, with certain species, may also mitigate against nitrogen loss by lowering the C:N ratio of crop residues (Sainju et al., 2005). This statement was supported by results reported by Hubbard et al. (2013) in the subtropical humid climate of Georgia, USA who observed increased soil carbon and nitrogen with cover crops that may support enhanced soil fertility and reduced erosion potential. Norris and Congreves (2018) further reported that integrating cover crops may help build soil health (nutrient cycling, aggregate stability, etc.) across climatic zones. Still, the selection of cover crop species or mixtures will be dependent upon several factors such as existing crop rotation and tillage practices.

Although several studies have shown positive impacts of cover crops, these effects varied considerably with soil type, elevation, and climatic conditions during the cover crop growth period (Poeplau & Don, 2014). In humid continental and subtropical climates, cover crops are typically grown during the relatively cold winter period that may also be more or less dry compared to the cash crop growing season. However, in the water-limited semiarid and arid climates, extremely limited precipitation and intermittent drought are common outside of the cash crop growing season that may be relatively more or less cold. In these climatic conditions, cover crop establishment after the main crop is quite difficult especially during periods of recurrent drought that are typical of such semiarid and arid regions (Idowu & Grove, 2014). For example, Holman et al. (2012, pp. 12–17) in semiarid southwestern Kansas, USA observed that cover crop establishment was critical for success and key criteria of cover crops species or mixture selection under similar arid and semiarid conditions. Across the world, farmers are working to incorporate cover crops into diverse cropping systems (Clay et al., 2020) for improved system sustainability under both conventional and organic management (USDA, 2010). Therefore, there is a great need for answers to uncertainties of cover crop species and mixture selection as well as how soil properties will be affected by cover crop management. Key concerns of cover crop adoption include which and to what degree soil nutrients may be affected as well as concerns of asynchronous nutrient capture and release with cover crops relative to cash crop demand. Additionally, water use by cover crops that will otherwise be available for cash crops is a major challenge affecting cover crop use in semiarid regions. While several studies and reviews demonstrated the effects of cover crops with diverse results, we are focusing on cover crops species selection and management under contrasting climates and soil types. This paper will be a review of cover crop types

Table 1
Crop types frequently used as cover crop with their common and scientific names (MCCC, 2014).

Type	Common name	Scientific name
Leguminous broadleaves	Clovers	*Trifolium* spp.
	Cowpea	*Vigna unguiculata*
	Faba bean	*Vicia faba*
	Hairy vetch	*Vicia villosa*
	Lentil	*Lens culinaris*
	Medics	*Medicago* spp.
	Pea	*Pisum sativum*
	Serradella	*Ornithopus sativus*
	Soybean	*Glycine max*
	Sunn hemp	*Crotalaria juncea*
Non-leguminous broadleaves	Buckwheat	*Fagopyrum esculentum*
	Flax	*Linum usitatissimum*
	Phacelia	*Phacelia tenacetifolia*
	Radish	*Raphanus sativus*
	Rapeseed	*Brassica napus*
	Safflower	*Carthamus tinctorius*
	Sunflower	*Helianthus annuus*
	Turnip	*Brassica Rapa*
Grasses	Barley	*Hordeum vulgare*
	Forage sorghum	*Sorghum biocolor*
	Millet	*Pennisetum glaucum*
	Oats	*Avena sativa*
	Rye	*Secale cereal*
	Ryegrass	*Lolium perenne*
	Triticale	*Triticosecale*
	Wheat	*Triticum aestivum*

and species with specific contributions to soil physical, chemical, and biological properties and conclude on the effects of cover crops under diverse climatic conditions. Key targeting words were used through online search engines to collect published results from agronomy, soil science, and cover crop scientific journals.

2. Single species cover crops

Many single species cover crops have been utilized to achieve specific goals in diverse cropping systems (Table 1). Grass species are desirable for their vigorous growth and persistent residues that decay slowly and provide substantial soil cover. Alternatively, broadleaf species may be more desirable for their quick decaying residues that may release captured nutrients back to the system more rapidly than grasses. Leguminous broadleaves are specifically utilized for their ability to fix atmospheric nitrogen in the nodules of the roots. Additionally, certain non-leguminous broadleaves like radish (*Raphanus sativus* L.) may serve to penetrate compacted layers of the soil surface and subsurface with their robust tap-root system (Dabney et al., 2010). The utility of each cover crop type is discussed below.

2.1. Grass cover crops

The root systems of grasses cover crops are generally fine, fibrous, and well adapted for reducing soil erosion and improving soil structure (Mcgourty & Reganold, 2005). Grass cover crop species include barley, forage sorghum, millet, oats, rye, ryegrass, triticale, and wheat. The ideal grass cover crop species are those that grow quickly to provide ground cover but may still be easily terminated by mechanical, chemical, or other means. Winter-kill is a popular non-chemical means of termination for some non-winter hardy grass cover crops. In some cases, mechanical termination may be preferred. For example, Bauer et al. (1993) found that burying of rye cover crops in a cotton (*Gossypium hirsutum*) production system did not limit nitrogen availability in their subtropical environment. Similarly, grass cover crops have been found to remove a significant amount of nitrogen from the soil, reducing nitrate leaching (Ruffo & Bollero, 2003), and Cline and Silvernail (2002) found that at the end of the production season, grasses recycled the remaining soil nitrate that may have otherwise leached out of the root zone. Further study has revealed the ability of grass cover crops to scavenge soil nitrogen and other nutrients and asserted that this ability is one approach to better manage surpluses of soil nutrients (Blanco-Canqui et al., 2015). On the other hand, several studies have shown such grass species to scavenge substantial soil nitrogen and occasionally limit availability to subsequent crops (Crandall et al., 2005; Pantoja et al., 2016; Ruffo & Bollero, 2003). Indeed, Crandall et al. (2005) reported that rye terminated later than optimal limited soil nitrogen and reduced subsequent corn (*Zea mays*) yields compared to earlier termination dates. This illustrates the importance of proper cover crop termination and planting dates to maximize the benefits of cover crops while limiting potential negative effects on the following cash crop.

In addition to their benefits for soil nutrient management, grass cover crops are effective for supporting beneficial soil macro- and micro-organisms while contributing to integrated pest management through suppression of some soilborne insects and diseases. For example, in a soybean-corn (silage) crop rotation in continental Iowa, USA, Korucu et al. (2018) found that a rye cover crop increased the population of earthworms (*Lumbricus terrestris*) 1.2 times compared to a similar system with no cover crop. In subtropical Georgia, USA, Glynn et al. (2004) observed suppression of cotton aphids (*Aphis gossypii*) with rye cover crops. Similarly, the rye cover crop contributed to suppressing both Columbia lance (*Hoplolaimus columbus*) and root-knot (*Meloidogyne incognita*) nematodes, when rye residues were mechanically incorporated or retained on the soil surface. Other parasitic nematodes, including the stubby root (*Trichodous obtusus*) and reniform (*Rotylenchulus reniformis*) types, have also been observed to be suppressed with rye cover crops. Additionally, lower nematodes densities were observed by Asmus et al. (2008) following Mulato grass hybrid *Brachiaria* or forage sorghum in cotton production systems of the subtropical and tropical climatic zones of Brazil. On the other hand, Phillips et al. (1971) reported that, in some circumstances, burying cover crop residues may provide a food base that could stimulate the growth of some pathogens. This illustrates the importance of proper species selection and tillage practices to maximize benefits and limit unforeseen negative consequences when integrating cover crops.

Important benefits in soil physical properties with grass cover crops include reduced bulk density, increased water stability and dry aggregates, as well as greater water infiltration and saturated hydraulic conductivity (Bruce et al., 1991; Reeves et al., 1992). Above all, grass cover crops are renowned for their capacity to prevent soil erosion by wind and water (Delgado et al., 1999; Kaspar et al., 2001; Langdale et al., 1991). For example, in temperate oceanic East Flanders and Flemish Brabant, Belgium, De Baets et al. (2011) observed the substantial fibrous root systems of rye and oats and speculated that these and other grasses species have the potential to help manage soil in agricultural landscapes susceptible to erosion. In some climates, grass cover crops have been found to increase soil water content by reducing evaporation and, therefore, conserving moisture for the subsequent crops (Blanco-Canqui & Ruis, 2020). Additionally, some have observed increased water holding capacity with cover crops including Bilek (2007) in the continental humid climate of Maryland, USA as well as Burke et al. (2021) in an irrigated production system in semiarid west Texas, USA. In the subtropical humid climate of South Carolina, USA, Bauer and Busscher (1996) reported a positive impact of rye cover crops on cotton yield compared to legumes. Still, Adhikari et al. (2017) observed no effects after 15 years when wheat was used as a cover crop in their cotton crop production system.

An additional benefit of grass cover crops is their capacity to suppress developing weed seedlings. With the potential to produce substantial biomass, grasses cover crops such as rye are frequently recommended as a component of integrated weed management plans (MacLaren et al., 2019; Osipitan et al., 2018). Further, highly productive grass cover crops are especially effective for weed suppression as they readily compete with weeds for light and nutrients. For example, Petrosino et al. (2015) in semiarid southwest Kansas, USA reported that winter and spring triticale cover crops were effective at reducing the number and biomass of Kochia (*Kochia scoparia*) plants. Similarly, Schappert et al. (2018) observed successful weed control with cover crops in temperate oceanic Baden-Württemberg, Germany.

2.2. Legume cover crops

Legume cover crops may include clovers, cowpea, faba bean, medics, peas, soybean, sunn hemp, and vetch. The primary advantage of legumes compared to grasses and non-leguminous broadleaves is their ability to obtain the nitrogen they need through a symbiotic relationship with bacteria in the nodules of the roots that fix nitrogen from the atmosphere. When utilized as cover crops, legumes may build soil nitrogen and supply it as a credit to subsequent crops. Still, different legume species may fix different amounts of nitrogen depending on cumulative biomass production. Those legumes producing more biomass will surely supply greater amounts of fixed nitrogen.

Table 2
Percent difference in soil nitrate (NO_3) and total nitrogen (TN) with legume cover crops.

Location	Soil Type	Climate	Cover crop	Soil Nitrogen		References
				NO_3	TN	
Georgia, USA	Gravelly clay loam	Subtropical humid	Crimson clover Hairy vetch		15%	McVay et al. (1989)
Georgia, USA	Sandy clay loam	Subtropical humid	Crimson clover Hairy vetch		26%	McVay et al. (1989)
Georgia, USA	Sandy loam	Subtropical humid	Crimson clover Hairy vetch		6%	Sainju et al. (2002)
Georgia, USA	Loamy sand	Subtropical humid	Crimson clover Sunn hemp		67%	Hubbard et al. (2013)
Emilia-Romagna, Italy	Silty clay	Subtropical	Hairy vetch		80%	Boselli et al. (2020)
Kansas, USA	Silt loam	Continental humid	Soybean Sunn hemp		22%	Blanco-Canqui et al. (2012)
Mississippi, USA	Silt loam	Subtropical	Pea Hairy vetch	40%	22%	Zablotowicz et al. (2011)
Montana, USA	Loam	Semiarid	Lentil	3%		Allen et al. (2011)
Montana, USA	Silt loam	Semiarid	Lentil Pea	8%		Burgess et al. (2014)
Montana, USA	Silt loam	Semiarid	Pea		11%	Engel et al. (2017)
North Dakota, USA	Silty clay loam	Continental	Faba bean pea	14%		Anderson et al. (2020)
São Paulo, Brazil	Clay	Tropical	Sunn hemp		10%	Rigon et al. (2020)

Legume cover crops may play a key role in system nitrogen management. Like all cover crops, legumes will utilize any available N and bind it as protein in the plant. In this way, cover crops may limit N losses through such processes as leaching or denitrification (Dabney, 1998). Still, legumes are most beneficial for their ability to contribute N to the system through symbiotic N fixation (Schomberg & Endale, 2004). Many studies have now demonstrated the capacity of various species of legume cover crops to improve N availability and use efficiency in diverse cropping systems (Table 2). For example, Sainju et al. (2002) reported that hairy vetch and crimson clover cover crops significantly increased soil N concentration on sandy soil in subtropical Georgia, USA. Similar results have been observed by others in additional subtropical, continental, and semiarid locations (Table 2).

After several decades of annual crop production, soil N and carbon may be depleted (Cambardella & Elliott, 1992). However, through their natural means of sequestering atmospheric N (Tairo & Ndakidemi, 2013), legume cover crops may play an important role in sustainable agriculture development. Through their symbiotic relationship with rhizobium, legumes may take advantage of N in the atmosphere that they then bind in their plant tissues. This N then becomes available to subsequent crops as the biomass of the cover crops decays. This is of great importance especially in areas where synthetic fertilizers are scarcely available or expensive (Dabney et al., 2010). Indeed, historically, many producers used crop rotation to integrate legumes into their cropping systems and depended on these legumes species as a major source of N to subsequent cash crops including corn (*Zea mays*), cotton (*Gossypium* sp.), sorghum (*Sorghum bicolor*), and wheat (*Triticum aestivum*) under diverse climatic conditions (Clark et al., 2007).

In subtropical Mississippi, USA, Seo et al. (2000) found that a hairy vetch cover crop was able to supply the equivalent of 50–155 kg ha^{-1} of N to the subsequent corn crop. Additionally, in continental Illinois, USA, Crandall et al. (2005) reported 150–250 kg ha^{-1} N fertilizer from hairy vetch to the following corn crops. Moreover, Schomberg and Cabrera (2001) identified legumes as good providers of N for cotton because about 50% of the nitrogen in the residue may be made available after just one week in their subtropical climatic zone (Fortuna et al., 2008). Similarly, in subtropical humid North Carolina, USA, Jani et al. (2016) reported that the rapid root decomposition of legume cover crops including pea, clover, and vetch could provide 17–37% of the nitrogen recommendation for corn. Similar results were observed by Humphreys (2016, p. 70) in subtropical Arkansas, USA who also observed substantial N accumulation in pea, clover, and vetch biomass. Bazen et al. (2007) stated in their review of the economics of cotton fertility that the amount of nitrogen fertilizer required following legume cover crops was substantially less or was eliminated compared to similar systems without such legumes (Bauer & Roof, 2004). This finding was supported by the results of Bauer et al. (1993) when peas were grown ahead of cotton in subtropical humid South Carolina, USA. Zablotowicz et al. (2011) observed that although legume cover crops may sequester substantial N, it may not be available to the subsequent cash crop during peak demand under all conditions (Larson et al., 2001).

2.3. Non-leguminous broadleaves cover crops

The non-legume broadleaves most widely utilized as cover crops include buckwheat, flax, phacelia, radish, rapeseed, safflower, sunflower, and turnip. Non-legume broadleaves are popular for many purposes including their rapidly decomposing residue for releasing nutrients as well as their potential for improving soil structure and reducing compaction because of deeper root systems. Several species of this type possess tap roots that work to create voids through the soil to improve aeration as well as water infiltration. Additionally, such broadleaf species are desirable for their rapidly decomposing residue compared to most grass species. This rapid decomposition helps to balance the goals of limiting nutrient loss while maintaining adequate fertility to meet the needs of subsequent cash crops. Furthermore, several *Brassica* species have been identified for their beneficial effect for controlling soil pests (Subbarao & Hubbard, 1996). Compounds called glucosinolates released from the decomposing *Brassica* residues have been shown to suppress several burdensome soilborne diseases including charcoal rot in soybeans (Sassenrath et al., 2019). Such processes are often referred to as biofumigation. Non-legume broadleaves including buckwheat, flax, phacelia, safflower, and sunflower are also desirable as a source of food for insect pollinators. This is especially important in annual cropping systems, orchards, and vineyards that include crops that rely upon pollinators.

Non-leguminous broadleaf cover crops have been frequently found to aid in optimized nutrient management. Through their ability to accumulate significant N similar to grasses, these species may aid in reducing nutrient losses. Still, with their low C:N residues, these species may also decompose quickly to supply substantial plant-available nutrition similar to legumes (Collins et al., 2007; Finney et al., 2016). Dean and Weil (2009) in subtropical Maryland, USA found that radish and rapeseed cover crops had greater than or similar N uptake to rye in the fall. However, as radishes were winter-killed, while the rapeseed and rye continued growing, greater N was available in the spring. Others have observed increased available phosphorus with similar cover crop species (White et al., 2016). In some instances, cover crops may be utilized in combination with manure application for optimized nutrient management (Cottney et al., 2020; Thilakarathna et al., 2015).

3. Multi-species cover crop mixes

Mixing of cover crop species has been suggested to obtain multiple benefits of different grass, leguminous, and non-leguminous broadleaf cover crops. The theory behind multi-species cover crop mixtures is that at least one or a few species will thrive every year and produce sufficient biomass for weed suppression as well as improvement of soil properties. In their review of cover crops and water quality, Christianson et al. (2017) reported that mixing of cover crops could be utilized to enhance soil fertility and reduce applied fertilizer needs for improved water quality in the Upper Mississippi River Basin, USA. To optimize nutrient management, it has been suggested that multi-species cover crops may balance goals of nutrient scavenging and timely release of nutrients to subsequent crops. Frequently, legumes are mixed with grasses to reduce the C:N ratio of cover crop residues for faster decomposition and reduced potential for excessive nutrient tie-up (Nielsen et al., 2015; Sainju et al., 2000; Treadwell et al., 2010). This was observed with a blend of oats and vetch in subtropical Eastern Cape, South Africa (Muzangwa et al., 2015) as well as with a blend of rye and vetch in subtropical Georgia, USA (Sainju, Singh, et al., 2007). Additionally, in continental Pennsylvania, USA, Finney et al. (2016) found substantial N scavenging with diverse cover crop mixtures. However, none of the mixtures tested in this study produced more biomass or scavenged more available N than the most productive monoculture. These results suggest that simple cover crop mixtures have the potential to provide some benefits to the component species at a reduced seed cost. However, cover crop species should be selected based on their ability to achieve specific goals which may not be fully realized in very diverse cover crop mixtures.

To manage for optimized C:N ratio cover crop residues, several management factors can be adjusted including species selection as well as planting and termination dates as they relate to the lignin and cellulose content of the cover crop biomass (Quemada & Cabrera, 1995). Warm weather can lead to rapid maturity and necessitate earlier termination dates. This is especially the case for grass cover crops which naturally possess a higher C:N ratio biomass especially during later stages of maturity. To mitigate this, earlier termination dates and blending of grasses with legumes (Clark et al., 1995; Doran & Smith, 1991) may lower the C:N ratio to a more desirable level around 25 C:N (Paul & Clark, 1996). Several studies have demonstrated the success of such practices, including Clark et al. (2007) as well as Vaughan and Evanylo (1998) with hairy vetch and rye in subtropical Maryland and Virginia, USA. Additionally, in subtropical Sainju et al. (2007a, 2007b) observed increased soil organic carbon with cover crops and greatest potentially mineralizable carbon with those cover crops including a mix of legumes. Additional strategies for managing cover crop mixtures for low C:N ratios include mowing and grazing (Vyn et al., 1999).

4. Cover cropping system benefits to soil health

Increasing attention has been given to cover crops by researchers, consultants, and producers (Reberg-Horton et al., 2011). Cover crop management may provide a wide range of benefits to soil's physical, chemical, and biological properties. These benefits may include increased soil organic carbon and available soil nutrients; reduced soil compaction and increased aggregation; as well as enhanced microbial activity, abundance, and diversity. Many studies have assessed the impacts of cover crops and tillage practices on soil quality using soil-quality indices. Jokela et al. (2009) found soil quality index (SQI) ranged from 80 to 87% and 73–83% in 0–5 cm and 5–15 cm depth respectively in a study of cover crop and liquid manure effect on SQI in the corn production system. Islam et al. (2021) revealed that management practices integrating conservation tillage with cover crops could help recover, keep, and build soil quality (SQ) to meet food security issues. Furthermore, Farmaha et al. (2021) analyzed soil nutrients in 196 fields in the southeastern United States and have reported soil health amelioration in no-tillage and cover cropping systems compared with the tillage system. Several studies have determined the influence of cover crops on soil properties across a range of soil types and climates. Below we attempt to review and discuss the results of potential effects of cover crops on soil physical, chemical, and biological properties.

4.1. Soil physical properties

Dynamic soil physical properties include bulk density, porosity, compatibility, wet and dry soil aggregate stability (Table 3), as well as water infiltration and hydraulic conductivity (Table 4) (Osman, 2012). Each of these may be altered through changes in long- and short-term crop and soil management. Bulk density, porosity, and penetration resistance are used as indicators of compaction or potential for soil compaction. Wet and dry aggregate stability indicates soil structural development and erodibility. Additionally, water infiltration and hydraulic conductivity directly measure the capacity of soil to absorb water and for that water to move through the soil pore space. Several researchers have discussed the potential for cover crops to improve these properties for enhanced soil function.

After some time of continuous crop production with regular tillage that breaks up soil aggregates, the physical quality of the soil may be sharply degraded to the point of significantly reduced crop productivity. Therefore, to ensure sustainable production, the amelioration of the physical characteristics of soil is a crucial challenge. For example, increased incidence of yield-limiting soil compaction has been observed as the size and weight of farm equipment continue to increase. Several studies have indicated the potential for cover crops to improve some physical properties (Lynch et al., 2012). Blanco-Canqui and Jasa (2019) in continental Nebraska, USA reported increased mean weight diameter of water-stable aggregates with grass cover crops though not with legume cover crops. In that study, cover crops were grown in a long-term no-till system on a silty clay loam which the authors speculated may have overshadowed the potential effects of cover crop management as no differences in soil bulk density or water infiltration were observed. Interestingly, in continental Kansas, the USA, Blanco-Canqui et al. (2011) observed a substantial (82%) increase in mean weight diameter with legume cover crops compared to fallow, suggesting that such legumes may be effective in some cropping systems and environments but not all (Blanco-Canqui & Jasa, 2019).

Table 3
Percent difference in water stable aggregates (WSA) and mean weight diameter (MWD) of wet aggregates with cover crops.

Location	Soil Type	Climate	Cover crop	WSA	MWD	References
Georgia, USA	Gravelly clay loam	Subtropical	Crimson clover Hairy vetch Wheat	6%		McVay et al. (1989)
Georgia, USA	Sandy clay loam	Subtropical	Crimson clover Hairy vetch Wheat	24%		McVay et al. (1989)
Illinois, USA	Silt loam	Continental	Rye Hairy Vetch	12%		Villamil et al. (2006)
Indiana, USA	Silt loam	Continental	Rye		40%	Rorick and Kladivko (2017)
Kansas, USA	Silt loam	Continental humid	Lentil Pea Triticale		50%	Blanco-Canqui et al. (2013a, 2013b)
Kansas, USA	Silt loam	Continental humid	Soybean Sunn hemp		82%	Blanco-Canqui et al. (2011)
Nebraska, USA	Silty clay loam	Continental	Rye Sorghum		31%	Blanco-Canqui and Jasa (2019)
Nebraska, USA	Silty clay loam	Continental	Hairy vetch Soybean		ns[a]	Blanco-Canqui and Jasa (2019)
Saskatchewan, Canada	Clay	Semiarid	Black medic		11%	Stainsby et al. (2020)
São Paulo, Brazil	Clay	Tropical	Sorghum Sunn hemp		20%	Rigon et al. (2020)
Tennessee, USA	Silt loam	Subtropical	Hairy vetch Wheat	7%	22%	Nouri et al. (2018)

[a] Not significant.

Table 4
Percent difference in water infiltration rate (WIR) and hydraulic conductivity (K) with cover crops.

Location	Soil type	Climate	Cover crops	WIR	K	References
Georgia, USA	Gravelly clay loam	Subtropical humid	Hairy vetch	59%		McVay et al. (1989)
Georgia, USA	Sandy clay loam	Subtropical humid	Hairy vetch Wheat	84%		McVay et al. (1989)
Georgia, USA	Loamy sand	Subtropical humid	Sunn hemp		5%	Hubbard et al. (2013)
Illinois, USA	Silt loam	Continental	Rye Hairy Vetch	ns[a]	ns	Villamil et al. (2006)
Missouri, USA	Silt loam	Subtropical	Rye	102%		Haruna et al. (2018)
Nebraska, USA	Silty clay loam	Continental	Hairy vetch Rye Sorghum Soybean	ns		Blanco-Canqui and Jasa (2019)
South Dakota, USA	Silt loam	Continental	Hairy vetch Rye	52%		Subedi Chalise et al. (2018)
Tennessee, USA	Silt loam	Subtropical	Hairy vetch Wheat	44%	107%	Nouri et al. (2018)
Texas, USA	Fine sandy loam	Semiarid	Rye	26%		DeLaune et al. (2019)

[a] Not significant.

Cover crops have the potential to improve soil structure as well as hydraulic properties (Tables 3 and 4). However, the extent to which cover crops may alter such properties may depend upon cover crop species and mixture selection, the duration of the growth period, the total amount of biomass produced, and environmental conditions (Blanco-Canqui et al., 2011; Blanco-Canqui & Jasa, 2019; Darapuneni et al., 2021; FAO, 2021). Darapuneni et al. (2021) identified grasses as having substantial impacts on soil physical properties in their arid climatic zone. These authors observed that sorghum-sudangrass was most effective for protecting the soil surface from wind erosion compared to either Japanese, pearl, or brown top millets because of the greater density and height of the sorghum–sudangrass biomass. In the subtropical humid climate of Georgia, USA, Hubbard et al. (2013) observed reduced bulk density and increased saturated hydraulic conductivity with cover crops in a conservation tillage system. The authors attributed these changes to the added soil organic carbon from decomposing cover crop residues. Still, in the subtropical humid North Carolina, USA, Wagger and Denton (1989) found limited impacts of cover cropping on soil porosity and hydraulic conductivity. In continental Missouri, USA, Cercioglu et al. (2019) observed greater saturated hydraulic conductivity and water retention with cover crops in a corn-soybean crop rotation on a claypan soil. Soil water retention and saturated hydraulic conductivity were also improved in silt loam and loam soils in subtropical Arkansas, USA after long-term cover cropping with crimson clover, hairy vetch, and rye (Keisling et al., 2014). Similarly, in subtropical Tennessee, USA, Nouri et al. (2018) observed the significant potential of wheat and vetch cover crops to improve soil physical properties including water infiltration, hydraulic conductivity, and aggregate stability in low-residue cotton production systems. Similarly, Wilson et al. (1982) and McVay et al. (1989) found increased water infiltration, soil structure, and porosity with cover crops compared to fallow in tropical Ibadan, Nigeria. and subtropical Georgia, USA, respectively. In continental Iowa, USA, Basche et al. (2016a) observed greater soil water holding capacity after long-term rye cover crop management. The authors attributed this to the substantial above- and below-ground biomass production of rye which was supported by findings from Reeves (1994; 1997) and results reported by Colla et al. (2000) in the Mediterranean climate of California, USA. However, in continental Nebraska, USA, Irmak et al. (2018) observed limited impacts of cover crops on soil bulk density, hydraulic conductivity, and water holding capacity.

Water stable aggregates are a frequently measured soil physical property for determining soil erodibility and soil health. Several studies have demonstrated that cover crops may improve soil aggregation utilizing different types of cover crop species and under different soil management practices and climatic conditions. For example, in tropical São Paulo, Brazil, Rigon et al. (2020) observed increased aggregation with millet, sorghum, and sunn hemp cover crops. These authors attributed these increases in aggregation to similarly observed increases in soil organic carbon. Additionally, greater proportions of water-stable aggregates have been observed with rye, hairy vetch, soybean, and sunn hemp cover crops in the continental climates of Illinois, Indiana, and Kansas, USA (Blanco-Canqui et al., 2011; Williams & Weil, 2004; Villamil et al., 2006; Rorick and Kladivko et al., 2017). Such increases in aggregation have been observed to facilitate greater soil macroporosity and improved water infiltration (Blanco-Canqui et al., 2013a, 2013b; Calonego et al., 2017). Notwithstanding, such benefits may be dependent upon soil texture with some soil types being more responsive to cover crop management than others (Blanco-Canqui et al., 2015). For example, in subtropical Georgia, USA, hairy vetch and crimson clover cover crops had a greater effect on water-stable aggregates of a sandy clay loam than a gravelly clay loam soil (McVay et al., 1989). Additionally, in some environments, cover crop mixture diversity has been observed to improve soil aggregation by increasing soil organic carbon contents (Saleem et al., 2020). The abundance of organic carbon or organic matter in the soil is directly linked to soil structure. Keisling et al. (1994) found in subtropical Arkansas, USA that, after 17 years of production, cover crops enhanced water retention capacity and were linked to similar increases in soil organic matter. Additionally, Nascente and Stone (2018) observed improvements in soil physical properties with grass and legume cover crop mixtures at their tropical location in Goiás, Brazil. In some environments, excess spring rainfall is a concern that may slow spring operations related to soil preparation and farm equipment inspection. Fall-planted winter cover crops may allow for earlier field entry with farm equipment by utilizing excess water for plant transpiration and improving soil strength through root growth. Daigh et al. (2014) and Qi and Helmers (2009) reported improved drainage and lowered soil water contents that provided for earlier field operations in continental Minnesota and Iowa, USA.

4.2. Soil chemical properties

Common soil chemical properties that have been investigated for their response to cover crop management include soil organic carbon (Table 5) or organic matter, nutrient concentrations (especially nitrogen (Table 2) and phosphorus), pH, cation exchange capacity, and electrical conductivity (Dharmakeerthi et al., 2005). Further, several studies have investigated the influence of cover crops on C:N ratio in the soil as an indicator of soil health and fertility (Bauer & Black, 1994; Follett & Peterson, 1988; Follett & Schimel, 1989). These properties are indicators of internal nutrient cycling and have been thoroughly investigated (Salinas-Garcia et al., 1997). Additionally, cover crops have been of interest for their ability to help mitigate the effects of climate change and global warming through their capability to sequester and fix the atmospheric C (DeLaune et al., 2019) and N (Moller et al., 2008; Wagger, 1989, pp. 27695–7643) and mitigate losses of CO_2 (Blanco-Canqui et al., 2013a, 2013b) and N_2O to the atmosphere. In temperate oceanic Washington state, USA, Kuo et al. (1997) observed increased soil organic carbon with cover crop species that produced residues with C:N ratios >30. Soil carbon is really important as its accumulation under cover crops decreases soil compatibility by improving the structure and decreasing soil bulk density. In subtropical Georgia, USA, Sainju et al. (2002) observed increased soil carbon and nitrogen concentrations with cover

Table 5
Percent difference in soil organic carbon (SOC) with cover crops.

Location	Soil type	Climate	Cover crops	SOC	References
Georgia, USA	Sandy loam	Subtropical	Crimson clover Hairy vetch Rye	9%	Sainju et al. (2002)
Kansas, USA	Silt loam	Continental humid	Lentil Pea Triticale	22%	Blanco-Canqui et al. (2013a, 2013b)
Kansas, USA	Silt loam	Continental humid	Soybean Sunn hemp	30%	Blanco-Canqui et al. (2011)
Mississippi, USA	Silt loam	Subtropical	Pea Hairy vetch	27%	Zablotowicz et al. (2011)
Nebraska, USA	Silty clay loam	Continental	Hairy vetch Rye Sorghum Soybean	ns[a]	Blanco-Canqui and Jasa (2019)
São Paulo, Brazil	Clay	Tropical	Millet Sorghum	28%	Rosolem et al. (2016)
Shaanxi, China	Silt loam	Semiarid	Huai bean Mung bean Soybean	13%	Zhang et al. (2019)
Tennessee, USA	Silt loam	Subtropical	Wheat	36%	Haruna (2019)
Texas, USA	Fine sandy loam	Semiarid	Hairy vetch Pea Radish Rye	74%	Lewis et al. (2018)
Texas, USA	Fine sandy loam	Semiarid	Rye	38%	DeLaune et al. (2019)
Washington, USA	Silt loam	Temperate oceanic	Rye Ryegrass	7%	Kuo et al. (1997)

[a] Not significant.

crops; the greatest carbon sequestration was observed for the rye cover crops with greater nitrogen accumulation with crimson clover and hairy vetch cover crops. Similar observations have been made in the subtropical regions of Tennessee (Haruna, 2019) and Kansas, USA (2011), and continental Illinois, USA (Villamil et al., 2006). However, most of these changes in soil chemical properties with cover crops are limited to the upper soil surface. Additional research may be needed to investigate the influence of cover crops on soil organic carbon stored in deeper soil depths and additional climatic zones. In the subtropical humid climate of Georgia, USA, Hubbard et al. (2013) investigated the effect of cover crops on soil surface C:N ratios in a sandy coastal plain soil. These authors reported increased soil carbon and nitrogen with sunn hemp and crimson clover cover crops and a shift toward lower C:N ratios. Similarly, Nascente et al. (2016) observed increased nitrogen availability to subsequent rice crops when sunn hemp was included in cover crop mixtures with millet. In addition to carbon and nitrogen, cover crops have been found to affect soil phosphorus, sometimes increasing and sometimes reducing availability to subsequent crops. For example, in continental Illinois, USA, Villamil et al. (2006) observed lower available P under corn following hairy vetch and rye cover crops. Similarly, Almeida et al. (2019) found that a ruzigrass (*Urochloa ruziziensis*) cover crop reduced available soil phosphorus to subsequent soybeans in their tropical environment.

4.3. Soil biological properties

Soil biological properties are very dynamic, and several studies have investigated the potential influence of cover crops on the activity, abundance, and diversity of such soil organisms as earthworms, nematodes, protozoa, fungi, and bacteria (FAO, 2021; USDA, 2019). Soil microbial activity has been linked to soil health as fungal hyphae as well as bacterial extracellular polysaccharides and hydrophobic compounds may contribute to improved aggregation and nutrient cycling (Capriel et al., 1990; Degens, 1997; Pervaiz et al., 2020). In continental Missouri, USA, Rankoth et al. (2019) quantified cover crop effects on soil microbial biomass and community structure in a corn-soybean rotation and found that microbial biomass was significantly increased and with only minor alterations in the microbial community structure (total fungi, total bacteria, rhizobia, gram (−) bacteria, and actinomycetes biomass). In continental Pennsylvania, USA, Finney et al. (2017) investigated the effects of eight fall-sown cover crop species grown as monocultures as well as in multi-species mixtures on microbial community structure and soil biological activity. The authors reported that individual cover crop species tended to favor particular microbial functional groups. For example, arbuscular mycorrhizal fungi were more abundant with oat and rye cover crops while non-arbuscular mycorrhizal fungi were more strongly associated with the hairy vetch cover crop. These results suggest that while there is a general link between cover crops, microbial communities, and soil health with cover crops generally promoting increased microbial biomass and activity, there may be species-specific cover crop rooting effects (Lehman et al., 2014). Cover effects on soil microbial community composition require further investigation (Finney et al., 2017). Of note, in the semiarid environment of USA Great Plains, Calderón et al. (2016) found that soil microbial community dynamics were more strongly associated with soil moisture than the presence of living plant roots. This suggests that in water-limited environments, soil moisture conservation may be more important than cropping intensification for promoting favorable soil biology.

Some studies have investigated cover crop effects on soil enzyme activities as a means of quantifying soil metabolic activity, plant and microbial biomass decay, as well as nutrient availability and cycling (USDA, 2019). For example, Mullen et al. (1998) observed increased arylsulfatase, L-asparaginase, acid phosphatase, and b-glucosidase enzyme activity with a hairy vetch cover crop in subtropical Tennessee, USA. Such was also observed in subtropical humid North Carolina, USA, where cover crops increased soil enzyme activities as well as bacterial populations and microbial biomass carbon (Kirchner et al., 1993). Similar results have been observed by others (Fernandez et al., 2016; Lupwayi et al., 2017). In semiarid Madrid, Spain, arbuscular mycorrhizal fungal populations were increased with winter barley cover crops (Hontoria et al., 2019). Similar observations were made by Lehman et al. (2014) with cover crops in continental Minnesota, Nebraska, and South Dakota, USA as well as subtropical humid South Carolina, USA. Further, in Mediterranean Tuscany, Italy, it was observed that cover crops contributed to increased arbuscular mycorrhizal fungi colonies in the subsequent corn crop roots (Njeru et al., 2014). This was significant as it has been one of the few observations of such effects.

In addition to their ability to promote beneficial soil microbes, cover crops have also been promoted for suppression of soil-borne pests and diseases (McNeill et al., 2012). In temperate oceanic Lower Saxony, Germany, Haj Nuaima et al. (2019) found that cover cropping with *Brassica* species reduced the abundance of bacteria, fungi, and nematode populations that are harmful to sugar beets (*Beta vulgaris*). Similar findings were reported by Detheridge et al. (2016) in temperate oceanic Ceredigion, Wales. Additionally, in continental Beijing, China, Li et al. (2016) observed inhibition of some nematode taxa (i.e., *Acrobeloides* spp.) which they attributed to toxic metabolites accumulated in cover crop biomass and released from cover crop residues. In a potato (*Solanum tuberosum*) production system, oat cover crops were found to reduce the abundance of soil nematodes as well as the bacteria responsible for common scabs of potato (Sakuma et al., 2011). Similar studies have reported the suppression of some fungal plant pathogens (Meriles et al., 2009; Perez-Brandan et al., 2013). Wang et al. (2018) observed that the residues of Jerusalem artichoke (*Helianthus tuberosus*) increased the activity of soil sucrase and urease enzymes, and that increased sucrase activity was negatively correlated with the abundance of soil-borne *Fusarium* pathogens in their tomato (*Solanum lycoperisicum*) production system. Others have made similar observations with different cover crop species and targeted crop pests (Chen, Chen, et al., 2020; Saleem et al., 2019; Treder et al., 2020).

In addition to beneficial soil fungi and bacteria, several studies have investigated the influence of cover crops on earthworm activity (Euteneuer et al., 2020; Roarty et al., 2017). Soil earthworms have been shown to assist with soil aeration, organic matter breakdown, nutrient cycling, and microbial biomass decomposition (Amador & Görres, 2007; Hickman & Reid, 2008). Still, the importance of their activities depends strongly on soil type and climatic conditions (Edwards, 1983; Euteneuer et al., 2020). In a continental climate of Indiana, USA, Willoughby and Kladivko (2002) observed a connection between earthworm abundance and increased soil aggregation and water infiltration. Cover crops were found to increase earthworm abundance but not species number in temperate oceanic Westmeath, Ireland. Similar responses were observed in continental Kansas, USA (Blanco-Canqui et al., 2011), continental Iowa, USA (Korucu et al., 2018), and tropical Réunion island, France (Boyer et al., 1999). The quality of cover crop residues may play a role in soil earthworm dynamics. Legume cover crops may support a greater abundance of such earthworm populations compared to grasses (Hendrix et al., 1992; Pelosi et al., 2009; Watkin & Wheeler, 1966). Interestingly, in continental Lower Austria State, Austria, Euteneuer et al. (2019) observed that increased earthworm populations in response to cover crops helped to reduce the fungal pathogen, *Sclerotinia sclerotiorum*, that causes *Sclerotinia* stem rot of soybeans, sunflower, and canola (*Brassica napus* subsp. *napus*).

5. Conclusion

Cover crops have the potential to provide many benefits to soil health in diverse cropping systems and climates. Numerous studies have demonstrated the importance of proper cover crop management for optimized benefits to soil physical, chemical, and biological properties. Cover crops may increase soil carbon and nitrogen as well as other nutrients and improve their cycling within cropping systems. The potential for cover crops to maintain and build soil fertility may allow for reduced reliance on synthetic fertilizer inputs. Long-term accumulation of soil carbon with cover crops may reduce compaction while increasing soil aggregation and water infiltration. Furthermore, cover crops may enhance beneficial soil microbial activity while suppressing some important soil-borne plant pests. However, their potential is still not fully understood in all cropping systems and climatic zones. Therefore, future research will be needed to further understand cover crop effects on soil properties as well as subsequent crop growth, yield, and overall cropping system profitability. As cover crop effects are generally not realized in the short-term, additional experiments will be needed to determine long-term effects of cover crops and their potential benefits to the long-term sustainability in diverse cropping systems and climates. Most of the research papers used in the review attributed the changes in soil health and properties to the cover crops while grown under some management practices that might have also affected the soil health and properties.

Author contributions

Study conception and design; writing-original draft preparation; writing-review and editing; visualization: K.K., K.D and S.C.A. All authors provided the final review and editing and have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

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Corrigendum

Corrigendum to “Critical review of the impact of cover crops on soil properties” [Int. Soil Water Conserv. Res. 10 (2022) 343–354]

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