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Effects of Cover Crops on Soil Physical Properties: A Comprehensive Review

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Abstract

The process of improving the soil's physical properties is essential to the conservation of soil. It is possible for cover cropping to enhance the soil's physical properties as well as its amount of organic matter. This, in turn, may prevent soil loss, which in turn can increase soil productivity and environmental quality. This article discusses the advantages of cover crops (CCs), for enhancing the soil's physical and hydraulic properties, as well as certain benefits that could arise in terms of soil conservation. According to the findings of the review, the presence of CCs in soil causes a reduction of roughly 4% in soil bulk density, an increase in macrospores of approximately 33%, and an increase in water penetration of up to 629%, in comparison to soil that does not include CCs. There have been reports that these changes led to a decrease in soil loss of up to 96%. It has been determined that there are certain information gaps in the area of knowing how CCs might alter the physical properties of soil. One of these knowledge gaps involves determining whether aboveground or *belowground biomass has a more significant role in the buildup of organic carbon. To further enhance soil physical properties and the related advantages, future study should concentrate on the interconnection of soil pores formed by CCs and the effect of CCs on heat transfer parameters.*

Keywords: Cover crops, sustainable agriculture, soil aeration, soil porosity, soil aggregation, soil permeability

1. Introduction

Increased agricultural food production is required by the expanding global human population and rising demand for food, which places significant pressures on the soil. This results in the adoption of management techniques that are more focused on boosting revenue than on preserving and enhancing soil quality. Increased usage of soil may result in a decline in its physical properties and eventual soil loss [1].Erosion and deterioration of soil is a major issue that affects the whole world although it is particularly severe in less developed tropical and sub-tropical nations. It is common for tropical and subtropical locations to have high temperatures, violent storms, and heavy rainfall, all of which may lead to an increase in the rates of erosion. These areas are especially prone to erosion because of the heavy rainfall that they get combined with the weak soils that they sit on [2]. For instance, between 1980 and 1990, the amount of soil area in Africa, Asia, and South America that was damaged by human-induced soil erosion was estimated to be 494, 748, and 243 Mha, respectively. These numbers demonstrate the critical need of taking immediate action in these places to combat soil erosion and to advance the adoption of sustainable soil management methods. The implementation of erosion control measures, the promotion of reforestation and afforestation, the improvement of agricultural practices (such as conservation agriculture and agroforestry), and the enhancement of awareness and capacity development among local communities and farmers should be the primary focuses of efforts [3]. This results in deterioration in both the quality of the soil and its production [4].

Utilizing cover crops (CCs) in crop rotation cycles is one strategy to decrease soil erosion and sustainably manage soil and its nutrients for greater production. Cover crops are very important for preventing soil erosion because they shield the soil surface from the damaging effects of both wind and water. Cover crops have thick foliage and extensive root systems, both of which serve to bind the soil particles together. This helps to prevent the soil particles from being detached and transported by the forces of erosion [5]. Cover crops are crops that are cultivated because of the multiple advantages that they bring. One of these benefits is that they protect the soil from being eroded by wind and water. Cover crops provide the function of a protective barrier, so defending the soil surface from the eroding effects of wind and water. The thick vegetation and ground cover that cover crops provide efficiently intercept rainfall, lowering the impact of raindrops and limiting soil detachment and transport. Cover crops assist to maintain the soil in places that are prone to wind erosion by lowering the average wind speed at the soil's surface. The plant canopy of cover crops functions as a physical barrier, avoiding the direct influence of wind on the soil and, as a result, decreasing the loss of soil that occurs as a result of erosion [5]. Both living CCs and their residues left on the soil can help minimize evaporation and help conserve soil moisture if the soil is covered. Cover crops have the potential to reduce the development of surface seals, which both increase the amount of water that can infiltrate the soil and reduce the amount of water that runs off [6]. It also improves soil porosity by creating biopores through roots and increasing soil activity[7]. There is evidence to suggest that cover crops improve soil physical properties as compared to no cover crops (NCCs), namely by reducing soil bulk density. By encouraging the development of soil aggregates and lowering soil compaction, cover crops help to enhance soil structure. Cover crop roots open up channels and pores in the soil, increasing porosity and decreasing bulk density. The presence of cover crops aids in preventing soil compaction and improves air, water, and root circulation across the soil profile [8], increasing water retention [9], saturated hydraulic conductivity [10], and water infiltration [11], and reduce soil loss [12]. The loss of organic matter from the soil may result from soil tillage. Tilling soil may alter the physical structure of the soil and hasten the decomposition of organic materials, particularly when done intensively or often[13]. For instance, the yearly average loss of organic carbon (OC) from the soil in two moldboard plowed watersheds was 187 kg C ha-^{1} and 165 kg C ha^{-1} for a period of 15 years (from 1972 to 1995) [14]. In a similar vein, Koch and Stockfisch[15] found that tiling enhanced the diffusion and breakdown of organic carbon, which ultimately resulted in a rapid decrease in soil organic carbon. The formation of humus, an inorganic substance that is resistant to decomposition, occurs during the gradual decomposition of organic material. According to Sollins et al., [16], humus has the ability to bind soil particles together, which in turn promotes soil aggregation and soil structure.

A natural binder, humus contributes to the formation of aggregates by bringing individual particles of soil together. It is full of intricate organic chemicals that combine to create colloidal complexes, which then bind to the individual particles of soil and form stable aggregates. Aggregation of soil is the process through which individual particles of soil come together to form bigger clumps or aggregates. When compared to the structures of the individual particles, the aggregates have a structure that is more stable. It is clear that humus plays a crucial part in the process of forming and stabilizing soil aggregates, which ultimately leads to an enhanced soil structure. Researchers and funding organizations have recently shown interest in cover crops, which has resulted in an increase in the amount of study conducted on the advantages of CCs and their use. For instance, Kladivko et al. [17] found that the potential for CC adoption in 10 counties located in five different states (Ohio, Indiana, Illinois, and Iowa), varied from 34 to 81%. This was a result of a greater knowledge of the function that CCs play in enhancing soil health metrics. Farmers' and producers' desire to implement conservation practices is highly related with perceived advantages, according to Arbuckle and Roesch-McNally [18], and this may have an effect on soil quality and production. However, our information on some of the mechanisms that contribute to the advantages of CC is still somewhat limited at the present time. The majority of research still does not provide clear evidence and sometimes contradict the findings of other studies. This study aims to reconcile the present data on the advantages of CCs in enhancing soil physical properties and soil conservation, while also noting specific gaps in our knowledge of current cropping systems that need to be remedied.

For the purpose of this review, previously published articles on CCs and soil physical properties were compiled. Results were tabulated, analyzed and synthesized before being presented. To find relevant published research, we conducted a worldwide search on the Web of Science and Google Scholar using subject keywords as search criteria. In the following sections, we will first discuss the physical properties of soil and CCs, and then we will discuss how CCs affect soil physical properties.

2. Soil Physical Properties

The terms "soil physical properties" and "soil physical attributes" refer to the physical characteristics of soil that affect its fertility, water availability, aeration, and overall health[19]. Soil porosity refers to the volume of pore spaces or voids in the soil, determining its ability to store and transfer water. Macropores and micropores drain at or below 3 cm when the water tension is between 3 and 300 cm [20]. The amount of water that leaves the soil during the hydrologic cycle is small, but the water in the soil regulates ecological processes. The presence of water in soil affects numerous soil processes, including erosion, chemical exchange, microbiological activity, transport of solutes and water, energy balance in the soil-plant system, and pedogenesis. It also determines plant development [21]. The impacts on soil are influenced by the relationship between water content and water potential, which can be used to estimate water retention capabilities. Soil water retention is defined by its water content and potential [22]. Although two soils may have the same matric potential, they can hold different amounts of water. Thus, the amount of water available to plants may vary between soils. The most crucial factor in agriculture is the water available to plants, which is the difference between a field's capacity and the point where plants wilt. To discover this relationship in non-saturated soil, the water characteristic curve is a popular method. This chart generally depicts the soil's volumetric water content as a function of potential. At times, it may also display the soil's volumetric water content as a function of matrix potential [23].

2.1. Cover Crops

Cover crops protect the soil during fallow periods by providing vegetative cover. According to Lu et al., [24], CC refers to any crop grown primarily for the purpose of soil health, weeds, water quality, biodiversity, pest and disease management. Most CCs are cultivated not only for their economic benefits but also for the benefits they bring to the environment. Cover crops are grown during dry times between harvests to benefit soil health, weed control, water quality, animal habitat, pest management, and ecosystem sustainability. They prepare soil for subsequent crops.

Throughout agricultural history, the cultivation of CCs has been a standard method for crop production [25]. Initially, cover crops were used as green manures and mulch, but they were later absorbed into the soil to improve fertility [26]. In the United States and many other countries worldwide, getting nitrogen through green manures or legume crops was widespread before the mid-20th century. Leguminous plants can fix nitrogen in the environment through a symbiotic interaction with nitrogen-fixing bacteria in their root nodules. After they are incorporated into the soil, these plants release nitrogen, providing a natural supply of fertility to future crops. At the moment, grain crop production is mostly dependent on the use of synthetic N fertilizers, which severely restricts the usage of green manure composting components.

Cover crops have the ability to control weed growth, fix nitrogen from the atmosphere, and sequester carbon in the soil. Natural weed control can be achieved by using cover crops that compete with weeds for resources and inhibit their growth, resulting in fewer weeds and the possibility of reducing pesticide use in the future. Many cover crops, especially leguminous plants, have the capacity to fix atmospheric nitrogen by coexisting symbiotically with bacteria that fix nitrogen. These microorganisms transform air nitrogen into a form that plants may use as they live in nodules on the roots of leguminous plants. The fixed nitrogen becomes accessible for succeeding crops when the cover crops are removed and absorbed into the soil, lowering the requirement for synthetic nitrogen fertilizers. Cover crops contribute to carbon sequestration by capturing atmospheric carbon dioxide (CO_2) through photosynthesis and converting it into plant biomass. When the cover crops decompose, the carbon is incorporated into the soil, contributing to the buildup of soil organic matter. Increased soil organic matter enhances soil fertility, improves soil structure, and promotes nutrient cycling. Moreover, sequestering carbon in the soil helps mitigate climate change by reducing the amount of CO_2 in the atmosphere. Leguminous cover crops have the unique ability to fix atmospheric nitrogen through symbiotic associations with nitrogen-fixing bacteria. This allows them to convert atmospheric nitrogen into a plant-available form and contribute significant amounts of nitrogen to the soil. On the other hand, non-leguminous cover crops can also play a crucial role in nitrogen management by immobilizing excess nitrogen from the soil, thereby minimizing nitrogen loss. Leguminous cover crops have specialized nodules on their roots that house nitrogen-fixing bacteria. Through a process called nitrogen fixation, these bacteria convert atmospheric nitrogen into ammonium, a form of nitrogen that can be readily used by plants. The nitrogen fixed by leguminous cover crops becomes available in the soil when the cover crops are terminated and their biomass decomposes. Studies, such as the one by Moller et al. [28], have estimated nitrogen fixation rates between 60 and 80 kg ha^{-1} for leguminous cover crops. Non-leguminous cover crops may nonetheless help with nitrogen management even if they do not fix atmospheric nitrogen. They accomplish this by immobilizing extra nitrogen from the soil. In their biomass, they store the available nitrogen that they have absorbed from the soil. By temporarily removing nitrogen from the soil, a method known as nitrogen immobilization lowers the possibility of nitrogen leaching and runoff. Non-leguminous cover crops eventually release the trapped nitrogen back into the soil, making it accessible to succeeding crops.

According to the findings of a research that was carried out by Fisk et al. [28], planting annual cover crops such as clover or medic beneath no-till maize led to a considerable decrease (ranging from 41 to 81%) in the quantity of winter annual weeds when compared to regions that did not have any cover crop. It is possible for cover crops to outcompete weeds for resources like as light, water, and nutrients, which will result in a reduction in the germination and development of weeds. Cover crops may offer thick growth and shade. The incorporation of cover crops into existing fields results in an increase in the amount of organic matter present in the soil. Cover crops provide a supply of organic material in the form of their biomass, which, when broken down, increases the amount of organic matter present in the soil. An increase in organic matter improves the structure of the soil, encourages the infiltration of water, lessens the soil's compaction, and raises the soil's ability to retain nutrients. Cover crops have the potential to significantly reduce the amount of soil compaction that occurs. The large root systems that they have assist to enhance the structure of the soil and provide channels for the circulation of water and air, which in turn helps to reduce soil compaction that is produced by heavy equipment and foot activity. Covers crops help reduce soil compaction, which in turn improves water penetration, root development, and the availability of nutrients. Cover crops help to reduce the amount of water and nutrients that flow off of agricultural fields. The canopy of the cover crop acts as a deflector for rain, lessening the force of individual raindrops as they hit the surface of the soil and therefore decreasing soil erosion. Cover crops have deep root systems, which improve infiltration and the soil's ability to store water, which in turn reduces the amount of water that runs off the soil. In addition, cover crops are effective in reducing non-point source pollution because they remove surplus nutrients from the soil, such as nitrogen and phosphorus, and stop those elements from moving into water bodies.

It has been found that the use of CCs in lieu of winter fallow led to a decrease in nitrate leaching of 65–70%. Cover crops play a crucial role in reducing soil erosion by lowering the amount of kinetic energy raindrops possess, thereby minimizing splash detachment. All these advantages are not possible with a single CC. However, from an agronomic and environmental standpoint, having a suite of CCs might provide the biggest advantages. Alfalfa (*Medicago sativa* L.), Austrian winter pea (*Pisumsativum* L. subsp. arvense), hairy vetch (Viciavillosa Roth), sunn hemp (*Crotalaria juncea* L.), and subterranean clover (*Trifoliumsubterraneum* L.) are a few of the most popular leguminous CCs that growers and researchers use. Cereal rye (*Secalecereale* L.), oats (*Avena sativa* L.), annual ryegrass (*Loliummultiflorum* Lam.), and Sudan grass (*Sorghum drummondi*) are a few of the most popular grass cover crops. Others include buckwheat (*FagopyrumesculentumMoench*), a cool-season annual broadleaf grain, and brassicas [29]. The discussion will focus on the positive effects of using CCs to improve soil physical properties, as well as their impact on soil productivity and environmental sustainability.

2.2. Cover crops and soil organic carbon

Organic carbon provides energy and nutrients to soil microbes. Increased organic carbon concentration in soil promotes microbial activity and the proliferation and variety of beneficial microorganisms. Microbes are critical to nutrient cycling, organic matter breakdown, and soil health. They aid in the decomposition of organic compounds, releasing nutrients for plant uptake and improving soil fertility overall. Organic carbon enhances soil water-holding capacity. It aids in the production of soil aggregates, resulting in the creation of pore spaces that allow for improved water infiltration and retention. Higher organic carbon content soils provide more water-holding capacity, lowering the danger of drought stress and increasing plant water availability.Organic carbon is a major contributor to nutrient cycling in soils. By functioning as a reservoir for important plant nutrients, it improves nutrient retention and availability. Organic carbon creates compounds with nutrients, limiting leaching and increasing plant accessibility over time, greater organic carbon content soils provide better nutrient availability, resulting in healthier plant development and greater agricultural yields. The presence of organic carbon in the soil is associated with enhanced agricultural production. Increased organic carbon levels increase soil structure, nutrient cycling, and water-holding capacity, all of which are necessary for optimum plant growth and development. Several studies, including the ones cited [31], have shown a favorable link between organic carbon and agricultural output. According to West and Marsoil[32], the accumulation of SOC leads to an increase in carbon sequestration and, as a result, environmental sustainability. It is beyond the scope of this text to provide a full explanation of the significance of SOC to the cycling of nutrients, the activity of microbes, and the capture of carbon dioxide. However, because of its significance in enhancing soil physical and hydraulic properties, the next paragraphs will explore the impact of CCs on the accumulation of SOC. Due to the degradation of belowground biomass in silt loam soils, [32] and [33] showed 26 and 36% greater SOC in CC plots compared to NCC plots (Table 1). In a similar vein, Kuo et al., [34]; Sainju et al., [35]; Sainju et al., [36]; Villamil et al., [37]; and Blanco-Canqui et al., [38] found 7, 12, 9, 9, and 30% higher SOC, respectively, with the usage of CCs in comparison to NCCs management. When compared with NCCs grown under the same tillage managements in a silt loam soil, Olsen et al., [39] found that CCs grown under no-tillage, chisel plow, and moldboard plow enhanced SOC by 30, 10, and 18%, respectively, when compared with NCCs grown under the same conditions. According to the findings of these experiments, cover crops were successful in regenerating soil organic carbon and recapturing soil organic carbon that had been depleted over a period of 12 years. On the other hand, Yang et al. [40] and Kasper et al. [41] found no significant difference in SOC between CC plots and NCC plots when they conducted their research in clay loam and loam soils, respectively.

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

Location	**Soiltexture**	**Covercrops**	**Depth**	**Decrease**	**Reference**
			cm	**%**	
Kansas,USA	Siltloam	Sunnhemp	0–7.5	4	[32]
Illinois,USA	Siltloam	Rye	0–5	6	[37]
		Ryeorhairyvetch		7	
		Ryeorhairyvetch-rye		7	
Alabama,USA	Sandyloam	Cerealrye,hairyvetch,	0–20	7	[46]
		crimsonclover			
Brazil	Clayloam	Millet	0–5	24	[12]
Missouri,USA	Siltloam	Cerealrye	0–10	3.5	[12]
Missouri,USA	Siltloam	Cerealrye,hairyvetch,Austrianwinterpea	0–30	3	[14]
Turkey	Clay	Hairyvetch,buckwheat,	0–20	14	[1]
		Hungarianvetch,phacelia			
Tennessee,USA	Siltloam	Winterwheat	0–6	12	[25]
Mississippi, USA	Siltloam	Winterwheat	0–5	3	[1]
Alabama,USA	Siltloam	Rye	0–10	ns	[5]
Wisconsin,USA	Siltloam	Rye, Kura clover, redclover,	0–5	ns	[9]
		Italianryegrass			
Maryland,USA	Sandyloam	Rye,forageradish, rapeseed	15–50	ns	[19]

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Brazil	Clay	Millet, sunnhemp,	0–5	ns	[15]
		sorghum–sudangrass			
Missouri,USA	Siltloam	Cerealrye	0–20	ns	[17]
Brazil	na	Millet,sunnhemp	0–10	ns	[21]
Missouri,USA	Siltloam	Cerealrye,hairyvetch,Austrianwinterpea	0–20	ns	[27]
Tennessee,USA	Siltloam	Hairyvetch,winter wheat	0–15	ns	[31]
Brazil	Loam	Oat	0–6	ns	[16]

In a research conducted by [42] on a loam soil, plots with CCs showed a 1.5- to 4-fold larger SOC after 6 years of establishment in comparison to plots that were under NCCs. The residue of CC that was left on the surface of the soil after CC treatment was responsible for the increased SOC that was achieved. It was thus determined that the cultivation of CCs was more successful in adding SOC to soils than the production of cash crops alone. In a study that came to a similar conclusion, both leguminous and non-leguminous CCs substantially enhanced soil organic carbon at a depth of 0 to 30 centimeters in loamy soil. In contrast to [42] attributed increases in SOC to carbon returned to the soil from cash crops, aboveground carbon-containing biomass, and weeds. They concluded that the Mediterranean climate simplifies SOC maintenance and growth.Indeed, there might be a variety of points of view and discoveries made about the variables that contribute to increases in the amount of soil organic carbon (SOC). In one more study [42] present conflicting perspectives on the dynamics of SOC in their respective research.Increases in SOC could be able to be linked to the carbon that is returned to the soil through cash crops, aboveground carbon-containing biomass, and weeds. In addition to the contributions that cash crops make to the input of carbon via their residues and root systems, weeds and aboveground biomass also play a part in the process of adding organic matter to the soil. Within this framework, the research reveals that management strategies and crop selections may have a considerable influence on the preservation and increase of SOC. In contrast to the findings of [42], this research emphasizes the significance of a climate similar to that of the Mediterranean in making the preservation and development of SOC easier. The particular climatic conditions that prevail in Mediterranean areas, such as hot, dry summers and moderate, rainy winters, are known to have an impact on the rates of organic matter decomposition and the dynamics of nutrients. During the summer, there is often less microbial activity, and during the winter, circumstances tend to be more favorable, both of which might contribute to the preservation and buildup of SOC.

A study on silt loam soil found that CCs affected SOC and carbohydrate content differently due to variations in their production. The rapid decrease in above-ground biomass of cover crops (CCs) below the soil surface, as indicated by an average half-life of 43.1 ± 8.6 days, suggests that the decomposition and incorporation of CC residues into the soil occur relatively quickly. Carbon cycling in the soil ecosystem relies heavily on the breakdown of above-ground CC biomass. Bacteria and fungi, for example, serve an essential role in decomposing organic materials, such as cover crop leftovers. The quick reduction in above-ground biomass is indicative of vigorous microbial activity and breakdown processes that are integrating the plant material into the soil. The breakdown of CC residues aids in the recycling and availability of soil nutrients. Above-ground biomass decomposition enables plant absorption of nutrients contained in the plant debris and subsequent use by soil microbes. The release of these nutrients helps maintain healthy soil and encourages plant development. Rapid breakdown of above-ground CC biomass aids in the synthesis and accumulation of soil organic matter (SOM). Decomposing cover crop residues provide organic carbon to the soil, which in turn enhances the soil's ability to store nutrients and water[34]. In addition, Liu et al., [43] found that after 2 and 8 weeks of incubation, the proportion of water-stable

2- to 6-mm aggregates in spring barley (*Hordeumvulgare* L.), cereal rye, and annual ryegrass CCs was much higher. The effects of CCs on SOC and carbohydrates were determined to be due to the quantity of C input from the various CCs used. The carbohydrates and polysaccharides in this fraction are the binding agents in the soil.

It is important to point out that the quality and quantity of biomass play a significant role in improving SOC [32], as well as microbial biomass [44], and that benefits like a reduction in bulk density can be obtained from SOC accrual [8]. Time is also another essential component in the SOC-building process. Because of the enhanced microbial activity, the incorporation of CCs into the crop rotation cycle has the potential to initiate higher mineralization as well as increased CO2 emissions during the cycle's early phases. Microbial immobilization rises with the passage of time, leading to an accompanying rise in SOC.

The concept of residue return and breakdown appears in the vast majority of the research that has been done on the effect that CCs have on the buildup of SOC. The aboveground and subterranean biomass are both included in these remnants. These wastes are broken down and organic carbon is added to the soil as a result of microbial activity, which is boosted by increased gaseous interchange, accessible water, and temperature and pH conditions in the soil that are suitable to growth. A measurement of whether kind of biomass, aboveground or belowground, plays a more significant role in the buildup of SOC is something that is lacking in the existing body of research. If this information were to be contributed to the existing body of literature, it might be utilized to enhance soil conservation methods while also advancing the state of knowledge about the dynamics of SOC within the soil. In addition, the texture of the soil may have some bearing on the availability of SOC. According to the findings of this research, clayey soils may have a lower availability of SOC when compared to silt loam soil. However, in order to assess the effect of soil texture and CCs on the availability of SOC, more study is required.

2.3. Cover crops and soil density

The bulk density of the soil is a crucial indication of the level of soil compaction, making it an essential measure of soil quality. Natural or pedogenic processes, such as the texture, mineralogy, and depth of the soil, may have an effect on it. Aside from natural causes, manmade influences, such as soil and crop management, are also known to have an effect on bulk density. The incorporation of CCs into crop rotation cycles plays an important part in determining the bulk density of the soil. There are a few different processes that are accountable for the effect that CCs have on the bulk density of the soil. When compared with soil minerals, CC residues often have a lower mass to volume ratio than their counterparts. Therefore, the ratio of mass to volume will be smaller in the soil if it includes a greater amount of leftovers. Additionally, the roots of live CCs are able to go deep into the soil. According to Chaudhari et al., [44], plant roots leave behind biopores that improve soil porosity and also diminish the mass-to-volume ratio of soils.

Blanco-Canqui et al. [38] investigated the impacts of CC in boosting no-till potential for enhancing soil physical properties over a 15-year period. The study's soil was a Geary silt loam (fine-silty, mixed, superactive, mesicUdicArgiustolls) with a 3% slope. The preferred CC was sunn hemp.Blanco-Canqui et al. [38] found that cover crops (CC) can improve soil physical properties over 15 years in Geary silt loam's 3% sloping field. Sunn hemp was the favored CC. Soil samples were collected at 0-7.5 and 7.5-15 cm. CC decreased bulk density by 4% at 0-7.5 cm depth compared to non-cover crops (NCC) plots. Hairy vetch and winter rye CCs enhanced soil porosity by decreasing bulk density and penetration resistance. Other studies also found that CC usage decreased soil bulk density by 3-24% compared to NCC usage due to CC roots and increased soil organic carbon (SOC).

Chen and Weil [46] found that forage radish (Raphanussativus L. var. longipinnatus 'Daikon') could penetrate sandy loam soils and relieve compaction at depths ranging from 15 to 50 cm in a research on root penetration through compacted soils. Also discovered comparable results. Human and mechanical traffic considerably increased soil bulk density, but CCs had no impact in alleviating bulk density on a sandy loam.

2.4. Cover crops and pore-size distribution

Cover crops have a variety of effects on the pore size distribution of soil. Increased SOC improves soil aggregation and stability, resulting in more prolific root development. This study focuses on macropores (>500-m radius), coarse mesopores (30- to 500-m radius), fine mesopores (5- to 30-m radius), and micropores (5-m radius) [47]. In a study on a silt loam soil,It has been found that cereal rye CC increased the proportion of macropores by 30%, averaged over two depths (0-10 and 10- 20 cm) 2 weeks after CC termination and spring tillage (compared to NCC management), most likely due to an increase in SOC and the activity of CC roots. This research indicated that the macropores formed by CC might last for a long period.

To a similar extent, Villamil et al. [37] observed that the usage of CCs resulted in considerable increases in the number of transmission pores (pores that are linked), which in turn mirrored changes in the pore-size distribution of a silt loam soil. In table 2, we see how the presence of CCs affects the pore size distribution depending on the location, soil texture, CC type, and soil depth. Also found that the presence of CCs considerably increased the macroporosity of a loam soil. Similarly, Garcia et al. [49] observed that the usage of CCs on a clayey soil enhanced macroporosity by 1–2% at the 0- to 5-cm depth owing to root activity. In contrast to the findings of Garcia et al. [48] found that the root morphology of CCs (leguminous vs. non-leguminous) did not have a significant effect on the macroporosity, pore morphology, and connectedness of the soil.Cercioglu et al. [49] studied 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 in a more recent research. On a 2,500-mm^2 region, CC plots had around 33% more macropores than NCC plots at all depths (0-10 and 10-20 cm). They also found that CC plots contained 50, 28, and 75% more macropores than NCC plots of miscanthus (*Miscanthusgiganteus* J.M. Greef&Deuter ex Hodkinson&Renvoize) and switchgrass (*Panicumvirgatum* L.). This shows that CCs, like perennial crops (miscanthus and switchgrass), may give comparable advantages in terms of enhancing pore size distribution.

TABLE2

Covercrop(CC)influenceonporesizedistributionbylocation,soiltexture,CCtype,andsoildepth.Pleasenotethatporesizediametersusedfortheclassificationofporesintomacropores,mesopores,andmicroporesvariedamongstudies

Location	**Soiltexture**	**Covercrops**	**Depth**	**Macropores**		**Mesopores**		**Micropores**		**Reference**
			cm	% increase	% decrease	% increase	% decrease	% increase	% decrease	
Missouri,USA	Siltloam	Cerealrye	0–20	30						[11]
Illinois,USA	Siltloam	Rye	3–10	29		6				[19]
		Ryeorhairyvetch		11		6				
		Rye or hairy vetch-rye		14		7				
France	Loam	Redfescue	0–10	67	–					[24]
		Bird’s-foot-trefoil		33	–					
		Alfalfa		50	–					
		Redfescue	10–20	–	67					
		Bird’s-foot-trefoil		12	–					
		Alfalfa		–	60					
Brazil	Clay	Sorghum,	0–5	2		Sudangrass				[29]
		Pearlmillet		2						
		Sunnhemp		1						
Missouri,USA	Siltloam	Cereal rye, hairyvetch ,	0–10and 10–20	33						[39]

		Austrianw interpea								
Missouri ,USA	Siltloam	Cerealrye	0–10	ns	ns	ns	ns	ns	ns	[12]
Nebraska,USA	Siltloam	Cerealrye	0–10	ns	ns	ns	ns	ns	ns	[38]

*Note.*NotethatsomestudiesreportdifferencesinporesizesatvariousdepthsOtherstudiesalsoreporteddifferencesinporesizesduetospecificCCs.ns=nosignificantdifferences.

[a]Macropore=>1,000µm.[b]Macropore=>50µm;Mesopores=0.5–50µm.[c]Macropores≥1,767µm.[d]Noporeclassificationprovided.

Abdollahi et al., [50] investigated the impact of CCs on the pore properties of a sandy loam soil and found that CCs enhanced air-filled macroporosity at -10 kPa and pore organization in soil when compared to NCCs. The conclusion was that CCs mitigated the impacts of a tillage pan. It has been also found that cereal rye CC substantially decreased soil bulk density and enhanced noncapillary porosities compared to NCC at the 2.5- to 7.5-cm soil level, even after numerous machine passes on a loamy soil. It was proposed that the strengthening impact of a network of continuous roots inside the soil may have reduced soil compaction. This shows that CCs have the potential to enhance soil quality.In contrast, Blanco-Canqui, [38] found that after two years of including cereal rye CC into a crop rotation cycle, overall porosity of silt loam soils did not alter. Furthermore, CC may take longer than two years to grow before its benefit on soil hydraulic characteristics may be detected.According to several contradictory data on the effect of CCs on pore size distribution, there are gaps in understanding the usage of CCs for enhancing field hydrology. To overcome these gaps, both the shape of CCs created pores and their interconnection should be assessed.

2.5. Cover crops and soil water retention

For the purpose of forecasting water storage, soil water retention curves are used. The soil's porosity, which may be affected by management measures such as cover cropping, is directly related to the soil's capacity to hold onto water. Increased water retention in the soil is a potential benefit of biopores produced by CC roots. There have been reports that cover crops enhance water retention at field capacity [9].. This increase was measured at water pressures of –10 and –30 kPa. This range of water potentials often coincides with the presence of coarse mesopores, which shows that the coarse mesopores formed by the practice of cover cropping have the potential to improve water storage at these pressures. In addition, Hubbard et al. [51] found that there was an 18% increase in water retention in CC plots on a loamy sand soil compared to NCC plots at water pressures of –30 kPa, as compared with NCC plots.Both Villamil et al. [39] and Basche et al. [9] found that the presence of CCs enhanced the amount of plant water that was readily accessible. Basche et al. [9] found that CC management on loamy soil substantially enhanced plant accessible water content by 21 and 22%, respectively, as compared to NCC management at depths of 0 to 15 centimeters and 15 to 30 centimeters. There is a correlation between a rise in the amount of organic matter in the soil [52] and changes in the aggregation of the soil [53]. Villamil et al. [37] indicated that CC management caused an increase in soil organic matter and aggregate stability, and that this affected water retention at field capacity. This was in comparison to NCC management.In contrast, Wardet al. [54] found that there was no change in water storage as a result of CCs in their research on the relationship between water balance and conservation agriculture in a climate typical of the Mediterranean. According to the findings of this research, the influence that CCs have on the amount of total evaporation throughout the summer and autumn seasons is rather little. However, CCs might have rare short-term effects on the rate of evaporation quickly after rainfall. According to the findings of these research, the incorporation of CCs into agricultural practices in places with a climate similar to that of the Mediterranean is very unlikely to affect water balance, but it may still improve the overall sustainability of agricultural practices. In a similar vein, Blanco-Canqui et al. [38] found that CC management did not have a significant effect on the amount of water that the soil was able to retain at field capacity and permanent wilting point. As a result, CC management did not result in an increase in the amount of water that was accessible to plants in these trials.

When attempting to use CCs in order to enhance the soil's physical attributes, climate is an essential underlying component that has to be taken into consideration. These contrasted outcomes witness to this. In semi-arid and dry conditions, the same action of CCs that improves soil water storage in humid and sub-humid areas may be responsible for probable drainage and increased evapotranspiration.

2.6. Cover crops and saturated hydraulic conductivity

According to Bodner et al., [55], pedogenic and anthropogenic influences have an impact on the saturated hydraulic conductivity (K_{sat}), a highly sensitive indicator of water flow that changes over time and space. Parent material and soil texture are examples of pedogenic variables that have an impact on K_{sat}, while different soil and crop management techniques are examples of human effects. Researchers Bodner et al.[56] found that CCs (phacelia [PhaceliatanacetifoliaBenth.], hairy vetch, rye, and mustard [Brassica rapa subsp. oleifera]) were responsible for 9.7 percent of the total variability in near-saturated hydraulic conductivity along a cover-cropped field slope. They reasoned that because CC roots may partially block pores, this must have an adverse effect on Ksat. According to Keisling, Scott, Waddle, Williams, and Frans (1990), when applied to an Arkansas silt loam soil, a rye-hairy vetch CC sequence resulted in a 166% increase in Ksat in the top 5 cm of soil, a 194% increase in the 5-10 cm depth, and a 359% increase in the 10-15 cm depth when compared with NCC treatment. When comparing a wheat (*Triticumaestivum* L.) and hairy vetch CC to fallow under a strip tillage system on a sandy loam soil, Wagger and Denton (1989) found no variations in soil porosity and K_{sat}.

There is evidence that the intensive rooting of rye CC may improve water permeability in corn fields [57]. For instance, Yu et al. [10] found that in a silt loam soil, CC root-induced improvements in hydraulic conductivity may reduce runoff after heavy rain by up to 17%.

2.7. Cover crops and water infiltration

When most fields remain fallow throughout the winter, it is possible to boost water transpiration by planting cover crops. As a consequence of this, there is potential for an increase in the amount of water that penetrates the soil. This is of utmost significance in regions that get very copious amounts of spring precipitation. According to Zhu et al., [12] research, this results in reduced runoff, a decrease in pollution from non-point sources, and, as a consequence, cleaner streams and rivers. In most cases, an increase in macropores brought about by CC roots leads to an improvement in water infiltration. Cover crop residue that is left on the soil surface may promote water penetration by minimizing soil surface sealing and surface water runoff. This allows for more water to be absorbed by the soil. In Brazil, Kemper and Derpsch[58] carried out an experiment on a clayey soil that belonged to two distinct soil orders (Oxisols and Alfisols) in order to evaluate the impact of cover crops (winter annual legume and rapeseed; B. napus L.) on infiltration. In comparison to wheat stubble, the data demonstrate that the CCs boosted the infiltration rate by 416 and 629% on the Oxisols and Alfisols, respectively. They believed that the biopores produced by the CC roots were responsible for this rise in penetration rate.

On an eroded Alfisol in southern Nigeria, Wilson et al., [59] found an increase in macropores and penetration with the application of CCs. After three years of farming, McVay et al., [60] used a sprinkler infiltrometer to determine the infiltration rate on a coastal plain soil in Georgia. According to the findings, no-till grain sorghum [*Sorghum bicolor* (L.)Moench] planted after hairy vetch CC had an average penetration rate of around 5.8 cm per hour. Infiltration rates were around 4.2 cm/h^{-1} after a wheat CC and 3.8 cm/h^{-1} after a winter fallow, respectively. According to Bruce et al.[61], the adoption of CCs boosted infiltration rate as compared to NCCs by 100 and 79%, respectively. In addition, Folorunsoet al. [62] found that CC plots had better rainfall infiltration than a fallow cycle. In comparison to NCC management in a rain-fed system, Haruna et al. [63] also showed enhanced water infiltration metrics in CC (cereal rye) on a silt loam soil. All of these show how CCs may enhance water penetration into the soil.

Blanco-Canqui et al. [38] found that cover crops (CC) can improve soil physical properties over 15 years in Geary silt loam's 3% sloping field. Sunn hemp was the favored CC. Soil samples were collected at 0-7.5 and 7.5-15 cm. CC decreased bulk density by 4% at 0-7.5 cm depth compared to non-cover crops (NCC) plots. Hairy vetch and winter rye CCs enhanced soil porosity by decreasing bulk density and penetration resistance. Other studies also found that CC usage reduced soil bulk density by 3-24% compared to NCC usage due to CC roots and increased soil organic carbon (SOC).

When comparing CC management to NCC management on a silt loam soil, Bilek (2007) found that the infiltration rate, cumulative infiltration, and hydraulic conductivity were all considerably higher under CC management. Similarly, Nouri et al. [64] observed that the usage of vetch and wheat CCs enhanced cumulative infiltration by 86 and 116%, respectively, compared with NCCs on a silt loam soil when the management technique was no-till. The increased porosity that was produced by the roots of the CCs was thought to be the cause of the improvement in cumulative infiltration that was observed.

According to the findings of Haruna et al. [63], CC management produced a considerably greater sorptivity parameter when compared to NCC management. The findings of this research revealed that the capability of CCs to lower nearsurface soil water content via transpiration might be essential in particularly wet early growing seasons. As a result, CCs may stretch the growth season of the cash crop by allowing farmers to plant earlier during rainy springs, which would result in a longer growing season for the cash crop. On the other hand, this very same occurrence may be harmful in areas that are semiarid and arid, as well as during the drier growing seasons in places that are humid and subhumid. However, Daigh et al. [65] argued that the changes in soil water content that occur between CC management and NCC management may not be large enough to impair crop output. Sims [66] and Gardner [67] claimed that despite the near-surface soil water transpiration by CCs, cash crop output could be maintained or enhanced by suitable species selection and optimum timing of CC termination. This could be done by reducing the amount of time that CCs were allowed to remain in the field.

2.8. Cover crops and heat transport

Heat movement in the vadose zone is an important aspect of soil physical properties, as it plays a role in the movement of water and nutrients, as well as in microbial activity and crop production. Heat transfer is likely to become an important component affecting agricultural production as a result of current changes in climate across the planet. According to Hopmans et al., [68], it is possible to determine heat transfer using thermal conductivity (λ), specific heat capacity by volume (CV), and thermal diffusivity (D) values.

There have been reports that management techniques that compress the soil increase because the of soil minerals is more than that of air and water [69]. This is because the of soil minerals is greater than that of air and water. In addition, research has shown that there is a significant positive link between SOC and CV [33]. This correlation is strongest between SOC and water content. Also it has been discovered that cover crops (CCs) such as hairy vetch, cereal rye, and Austrian winter pea had a 13% and 16% higher coefficient of variation (CV) at saturation and -33 kPa soil water pressure, respectively, compared to no cover crop (NCC) management. This was due to the higher water content at specific matric potentials and soil organic carbon (SOC) in CC compared to NCC management. In a laboratory-controlled setting, CCs may help buffer the soil against high heat changes. However, CCs did not significantly affect bulk density in either CC or NCC plots [32]. Meanwhile, Sindelar et al. (2019) found that CCs did not affect the thermal characteristics of silt loam soil, likely because CCs did not influence soil water content, bulk density, or SOC. Thermal characteristics were more closely linked to bulk density and water content than SOC. Further research is needed to investigate the impact of CCs on these critical heat transfer parameters and to assess the feasibility and advantages of employing CCs to buffer against excessive soil heat change in a changing global climate on other soil textural classifications.

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

[32] found that cover crops (CCs) like hairy vetch, cereal rye, and Austrian winter pea had a higher coefficient of variation (CV) at saturation and -33 kPa soil water pressure, respectively, when compared to no cover crop (NCC) management. This was due to higher water content at specific matric potentials and soil organic carbon (SOC) in CC compared to NCC management. CCs may help buffer the soil against high heat changes in a laboratory-controlled setting. However, CCs did not significantly affect bulk density in either CC or NCC plots [32]. Meanwhile, CCs did not affect the thermal characteristics of silt loam soil, likely because CCs did not influence soil water content, bulk density, or SOC. Thermal characteristics were more closely linked to bulk density and water content than SOC. Further research is needed to investigate the impact of CCs on these critical heat transfer parameters and to assess the feasibility and advantages of employing CCs to buffer against excessive soil heat change in a changing global climate on other soil textural classifications.

According to Dabney et al. [5], cover crops have the ability to prevent soil loss in two different ways: as a living canopy and as mulch. According to Haramoto and Galsoilt[70], the amount of protection provided by CCs' canopies is contingent on the kind, quality, and stand of the crops that are used and might change from season to season. The efficiency of the mulch is also dependent on the quality and amount of residues that are left on the surface of the soil. Because of this, the efficiency of CCs in preventing erosion is not only contingent on the kind and quality of the CCs themselves, but also on the time of year in which they are cultivated. This increased surface cover has the potential to cut down on soil loss and make agriculture more sustainable.According to a research by Folorunso et al. [62] on the impact of winter CCs on soil surface strength and infiltration rate, bromegrass (Bromus spp.) and strawberry clover (*Trifoliumfragiferum* L. ssp. Bonanni (C. Presl) Sojak.) CCs decreased soil surface strength by 38–41% in comparison to NCC. As a result, as compared to NCC, the steady infiltration rate and cumulative water infiltration both increased by 37.41% and 20.101%, respectively. According to Adler et al. [71], cereal rye CC is a useful strategy for lowering soil and nutrient loss in a no-till tile-terrace field because it increases infiltration rate. In order to decrease soil loss and winter nutrient loading into streams and rivers, recommended using CCs.

Reicosky and Forcella[72] examined the function of CCs in limiting wind and water erosion and C input to improve soil quality in their assessment of the relationships between CC and soil quality in agroecosystems. According to reports, CCs' C input may assure long-term economic advantages with no negative influence on the quality of soil, water, and air since the SOC can enhance soil structure, temperature, aeration, and water penetration and storage. Additionally, some CCs may have allelopathic advantages that enhance soil aggregation, encourage a healthy soil, and reduce the need for pesticides and herbicides while lowering off-site pollution.Shipley et al., [73] investigated how winter cover crops, such as hairy vetch, red clover, cereal rye, and annual ryegrass, may absorb leftover nitrogen fertilizer and reduce N losses. After 336 kg N ha^{-1}, the average N intake for cereal rye, annual rye, hairy vetch, and crimson clover was 48 kg N ha 1, 29 kg N ha^{-1}, 9 kg N ha^{-1}, and 8 kg N ha^{-1}. According to the % recoveries of fall N in the aboveground dry matter, CCs recovered more fall N than native weed fallow, which may enhance the quality of the water. Similar to this, CCs (winter wheat and cereal rye) scavenged an average of 200 kg N ha-1 when planted in vegetable potato (*Solanumtuberosum* L.) systems with significant residual soil NO3-N, according to a ten-year research by Delgado et al. [75]. These CCs were also attributed with recovering NO3-N via their root systems from subterranean water sources.Researchers Haruna and Nkongolo[75] investigated the effect that cereal rye CC has on the availability of nutrients. It was shown that after three years, the availability of phosphorus in plots managed with CC was 14% higher than in those managed with NCC. The majority of phosphorus is lost as particulate matter, hence Haruna and Nkongolo[75] ascribed the increased amount of phosphorus under CC management to the advantages of CC for soil conservation. The implementation of some conservation methods may be rather pricey, and the potential economic return to the producer may not be immediate or direct in nature. It is possible that a land user will not be instantly eager to commit some resources to aid "anonymous" folks [76]. This is because the majority of the effects of soil erosion are felt downstream or near to streams. In many poor nations, agriculture is mostly subsistence farming, and it is dependent on rain for much of its water supply. Economics may be a challenge in many countries. Majority of farmers in poor countries do not have access to the financial resources necessary to apply conservation techniques. Farmers in industrialized nations are more open to the idea of incorporating CCs into their cropping systems if doing so would enhance their competitive economic position.

According to Dumanski et al. [77], many direct land users have a traditional approach to their work and may be hesitant to give up activities like residue clearance and tillage that have been utilized by past generations and have contributed to increased erosion. In accordance with human nature, it is preferable to remain inside one's established routine rather than face the uncertainty that comes with making a transition. One method for the preservation of soil is the use of cover crops.Only after CCs have been effectively managed and have reached their full potential will it be possible to reap the advantages that are highlighted in this study. No tilling, timely planting, and timely termination are all important parts of the careful management of CCs. For instance, Munkholmet al. [78] found that a weak soil structure caused by long-term (thirty years) moldboard plowing affected the efficacy of CC (oat and spring barley) in restoring the soil's physical qualities. In addition late planting considerably lowered the development of cereal rye CC, which in turn reduced the hydraulic advantages of cereal rye CC. Early planting (for example, seeding the CC into standing cash crops) was mentioned as a potential way to increase the advantages of the CC. Prompt termination of conservation contracts (CCs) may boost both water conservation and the yield of cash crops. If not properly managed, cover crops have the potential to dry up soils and even lower the soil's water content during drought years [5]. According to Tillman et al. [79, some might potentially bring new illnesses or pests to a field. It may take many years to properly build a good CC management system. Consequently, in order for CCs to be successful, considerable planning is required.

Conclusion

The need to produce food and fiber for an ever-increasing world population has resulted in the adoption of more labor-intensive agricultural methods. These practices have led to the conversion of forested areas and other less productive terrain into farmland, which in turn necessitates the use of intense tillage and fertilizers. Intensive farming that does not make use of measures of conservation results in soil erosion, the degradation of soil structure and the soil biotic community, excessive sediment and nutrient loading in streams, and is a primary source of hypoxic zones in a great number of estuaries and marine gulfs all over the globe. They also contribute to the depletion of soil and nutrients on agricultural land. Degraded soils result in decreased land productivity, which in turn necessitates the use of more land for the production of food and fiber.In this paper, both older and more recent research on the use of CCs for enhanced soil physical characteristics and soil conservation, and subsequently increased land productivity, soil health, and environmental advantages, were analyzed and discussed. According to the research, soils containing CCs exhibited higher SOC levels, more macropores, improved water retention, and lower runoff rates caused by intense rainfall. All of these positive effects on the soil may lead to improvements in farming systems and the overall sustainability of the ecosystem.

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