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Fertile and physical evaluation of soil cultivated with cover crops: A review

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Abstract

Plants produced primarily for the advantage of the soil instead of for crop production (CP) are known as cover crops (CCs). Usually, plant them during the off-season, a time when main crops aren't grown. The main purposes of CCs are to improve soil health (SH), enhance water movement, prevent soil erosion, manage weeds, and increase biodiversity. CCs play a crucial role in sustainable agriculture by maintaining and improving SH and soil productivity (SP). Farmers have shown reluctance toward adopting CCs due to concerns about potential negative impacts on agro-ecosystem services, management challenges, and economic losses. However, studies indicate that CCs offer significant benefits, particularly in improving soil moisture (θ) and water penetration, especially through deep-rooted varieties. While CCs can enhance tillage and bulk density (ρ_b), their impact on soil organic matter (SOM) varies with soil type, topography, and climatic conditions. The integration of CCs into farming systems shows promise, particularly in diverse environments, for contributing to sustainable agricultural practices. However, it's still challenging to develop CCs following the principal crop in dry and semi-arid regions. Therefore, to maximize the advantages of CCs while minimizing any possible disadvantages, customized methods, and creative techniques are needed. Soil pH and texture are the most stable and essential elements to evaluate when analyzing soil fertility and physical attributes. These characteristics provide a foundational comprehension of the soil's identity, aiding preliminary decision-making. The enduring impacts of cover crops (CCs) on these characteristics are substantial, possibly modifying pH levels and soil texture over time. Although soil texture stays relatively stable over long durations, ρ_b and structure are crucial in influencing other physical properties. These parameters significantly influence soil aeration (a), θ , and root penetration (r_pD), which in turn influences the overall health and production of the soil. This review paper aims to identify cover crops and illustrate their advantages concerning fertile and physical evaluation.

Keywords: Cover crops, soil physical evaluation, soil fertile evaluation, benefits of cover crops

Introduction

The incorporation of CCs into farming systems produces both internal as well as external the expenses and advantages on the farm. The advantages include enhanced insect control, soil quality (SQ) and water quality (WQ), nutrient cycling efficacy, and cash crop (CCy) yield. Increased direct costs, potential income loss from competition with more profitable crops, difficulty in predicting soil N mineralization, delayed soil warming, and production costs are all costs associated with the adoption of CCs. The advantages of the CCs are more apparent in the majority of irrigated systems. For years, it has been a standard practice in agricultural production to hatch CCs (Reeves, 1994) ^[1]. Initially, CCs were cultivated as green manure crops, as sources of vegetation, and to enrich soil. Subsequently, CCs were incorporated into soils to enhance fertility (Kaspar and Singer 2011) ^[2].

Improved environmental conditions and SQ can lead to improved crop productivity (CP) in CCNs. CCs have many uses and enhance soil properties. Crop rotations are important in controlling pests, promoting nutrient mineralisation, suppressing weed establishment and increasing SOM. Application of cover crops (CCs) needs to be supported by ongoing research and sound management to take full advantage of these benefits. A global resurgence of CCs, an age-old approach, has been the consequence of the increasing visibility of conservation agriculture practices that support ecosystem services and enhance sustainable agriculture (Romdhane et al., 2019) ^[3]. The primary objective of the CCs is to enhance and protect SH (Benedict, et al., 2014) ^[4]. They can be incorporated into the soil as "green manure" or persist on the surface as mulches,

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whether they are living or dead (Benedict, *et al.*, 2014; Finney, *et al.*, 2017) ^[4, 5]. Cover crops (CCs) are plants that are cultivated in close proximity to protect and enhance soil quality during the intercrop season or in inter-tree intervals in plantations (Fageria *et al.*, 2005) ^[6]. The cover crops may consist of a variety of vegetation, but the majority are legumes or grasses that are not legumes.

CCs are a viable and sustainable agricultural method to enhance SH and crop performance. They are cultivated to preserve SQ by preventing erosion and nutrient leaching or runoff, inhibiting weed growth, facilitating carbon (C) sequestration, reducing soil compaction, and strengthening soil structure, water infiltration (I), and $\Lambda_{\text{p}}\Delta$: , while also promoting soil microbial populations (Scavo *et al.*, 2022; Unger and Vigil, 1998) ^[7, 8]. For CCs to be successful and context-specific, management techniques and CCs selection are essential. Benefits like nutrient transfer for CCy are often associated with CCs' positive effects on soil characteristics, which function as indicators of SQ. As a result, CCs may provide extra indirect advantages to crops, such as stimulating root growth, especially in fruit orchards (Scavo *et al.*, 2022) ^[7]. Erenstein (2003) ^[9] Advocated for the use of CCs as mulches to enhance soil and water conservation, emphasizing the need for early site preparation and crop establishment. To ensure the socio-economic viability of mulching, adoption should occur through a gradual process that includes educating farmers, securing funding, tailoring practices to local conditions, making improvements, and reforming institutions. This approach will ensure farmer involvement, community support, and thorough safeguarding of natural resources.

This paper emphasizes the advantages of CCs in improving the assessment of soil fertility and the evaluation of soil physical properties.

CCs and Their Variety

CCs are numerous and diverse in families (Table 1). Leguminous CCs tend to be slow-growing and involve significant establishment costs. At the same time, they contribute nitrogen to the soil, produce highquality residues in modest quantities (0.5-4 Mg ha⁻¹), and create favorable conditions for beneficial insects. Brassica plants produce residues rich in glucosinolates (2-6 Mg ha⁻¹), which suppress plant-parasitic nematodes and soilborne pathogens. Among CCs options, leguminous CCs stand out as the most reliable for increasing CCy compared to fallow land or other types. When soil pests severely limit CCy, incorporating leguminous CCs is worth considering. Cereal CCs provide the greatest biomass production (BP), making them the best option fo rapidly increasing SOM. Combinations of leguminous and cereal cover crops or brassica and cereal cover crops show promising results in a variety of ecological settings (Snapp *et al.*, 2005) ^[10].

In traditional tillage systems, CP increased by only 2%, while in reduced-tillage organic systems, it increased by as much as 24% when soil was overseen with plant cover crops such as hairy vetch, ordinary vetch, and white tarragon (Wittwer *et al.*, 2017) ^[11]. Improved the soil's characteristics and aggregate soil ecosystem services are indicated by increases in soil microbial populations. The cultivation and integration of CCs have been demonstrated to substantially increase soil micrograms in specific research studies (Vukicevich *et al.*, 2016) ^[12]. In accordance with a comprehensive research study, the incorporation of a variety of cover crop species, such as triticale,vetch, rye, bean,phacelia , faba radish, and pea, resulted in a substantial increase in the diversity and quantity of microorganisms that inhabit the soil (Schmidt *et al.*, 2018) ^[13]. Research also showed that soil treated with a mixture of oats and radishes, or oats, radishes, and vetch, The bacterial phospho fatty acid concentrations increased by 6.8%. and enzyme activity by 20% (Chavarría *et al.*, 2016) ^[14].

The primary categories of regularly cultivated CCs worldwide are leguminous , grass, and non-leguminous broadleaf plants. The decomposition and substantial soil coverage of grass species are highly valued, while broadleaf species are employed for their rapid decay and the ability to enrich the soil with residues, whilst leguminous species are employed for their N-fixing capabilities. Incorporating CCs into traditional agricultural systems may decrease *ph* and enhance soil structure and hydraulic characteristics, hence promoting more I and θ . Additions of crop residues from CCs may improve the accumulation of SOC and N, in addition to increasing the accessibility of phosphorus, potassium, iron, magnesium, and calcium in specific soil types under specific climatic conditions (Koudahe *et al.*, 2022) ^[15].

The leadership of CCs between CCy is a classic agricultural strategy that is currently garnering global attention (Romdhane *et al.*, 2019) ^[3]. Any plant species that are used for purposes apart from producing grain or fodder are considered CCs; they are often divided into three categories: grasses, non-leguminous broadleaves, and leguminous broadleaves. According to SSSA, CCs are used to protect and improve the soil in between yearly crop cultivation or between grapes in winemakers and trees in forests (Fageria *et al.* 2005) ^[6]. Many of the benefits of CCs may be realized only with correct administration. The successful application of CCs requires careful preparation and the choice of suitable kinds, seeding rates, planting seasons, terminate phases, and termination processes (Wortman *et al.*, 2013; Alonso-Ayuso *et al.*, 2014) ^[16, 17]. Termination strategies, termination stages, and species selection are the most critical components of management techniques that are essential for optimizing CCs to prevent nutrient immobilization and competitiveness with subsequent organisms, while simultaneously providing numerous benefits CCy (Wayman *et al.*, 2015) ^[18].

Table 1: Some cover crops (CCs) used in previous studies: prepared by the authors

Crop Name	Scientific name	[Reference]
Alfalfa	Medicago sativa	(Adetunji <i>et al.</i> , 2020) ^[19]
Cowpea	Vigna unguiculata	
Barley	Hordeum vulgare	
Crimson Clover	Trifolium incarnatum	
Faba Bean	Vicia faba	
Oat	Avena sativa	
Oilseed Radish	Raphanus sativus	
Pea	Pisum sativum	
Rye	Secale cereal	
Ryegrass	Lolium perenne	

Soybean	Glycine max	(M. C. C. C., 2014)
Serradella	Ornithopus sativus	
Sunn Hemp	Crotalaria juncea	
Triticale	Triticosecale	
Vetch	Vicia villosa	
Wheat	Triticum aestivum	
Buckwheat	Fagopyrum esculentum	
Clovers	Trifolium spp.	
Flax	Linum usitatissimum	
Forage Sorghum	Sorghum bicolor	
Hairy Vetch	Vicia villosa	
Medics	Medicago spp.	
Lentil	Lens culinaris	
Phacelia	Phacelia tenacetifolia	
Millet	Pennisetum glaucum	(Haruna et al., 2017) ^[20]
Safflower	Carthamus tinctorius	
Radish	Raphanus sativus	
Turnip	Brassica Rapa	
Sunflower	Helianthus annuus	
Cereal Rye	Secale cereale	
Austrian winter pea	Pisum sativum subsp. arvense	
Hairy Vetch	Vicia villosa subsp. Villosa	
Winter Wheat	Triticum aestivum	
Annual Ryegrass	Lolium multiflorum	
Hairy Vetch	Vicia villosa Roth	
Crimson Clover	Trifolium incarnatum	
Sunn Hemp	Crotalaria juncea	(Haruna, 2019) ^[21] (Kuo et al., 1997) ^[22] (Sainju et al., 2002) ^[23] (Blanco-Canqui et al., 2011) ^[24]
Rye Grass	Lolium perenne	
Crimson Clover	Trifolium incarnatum	
Durum Wheat	Triticum durum Desf.	
Trios 102 'Trios'	Triticale × Triosecale	
Italian Ryegrass	Lolium multiflorum	
Millet	Pennisetum glaucum	
Kura Clover	Trifolium ambiguum M. Bieb.	
Red Clover	Trifolium pretense	
Rapeseed	Brassica napus	
Forage Radish	Raphanus sativus var. longipinnatus	
Ruzigrass	Urochloa ruziziensis	
Sorghum - Sudangrass	S. bicolor × S. sudanense (Piper) Stapf	
Red Fescue	Festuca rubra	(Chen and Weil, 2010) ^[29] (Garcia et al., 2013) ^[30] (Carof et al., 2007) ^[31] (Wilson et al., 1982) ^[32] (Folorunso et al., 1992) ^[33]
Bird's-Foot-Trefoil	Lotus corniculatus	
Stylo	Stylosanthes guianensis	
Strawberry clover	Trifolium fragiferum	
Bromegrass	Bromus inermis	

CCs and soil Physical Evaluation (SPE)

The soil's physical properties, including θ , ρ_b , and porosity (n), influence its quality. Based on these characteristics, it may determine how efficiently the soil stores water and nutrients. The physical characteristics of the soil influence both the movement of nutrients and water to the rhizosphere and the animals that live in it. When it comes to flow (v) and I , n is the most significant physical characteristic. The soil pore categorization (Soil Science Society of America, 2008) ^[34] states that macropores and micropores drain when the tension is less than 3 cm and 3 to 300 cm, respectively. Micropores store water that plants may access, but macropores and mesopores allow water to drain naturally. Macropores have a high level of pore consistency. The mesopore system, on the other hand, contains fewer continuous pores and more twists and bends (Luxmoore, 1981; Messing and Jarvis, 1993) ^[35, 36].

Currently, multiple research have proved the effectiveness of CCs in agricultural output, with many of them concentrating on soil physical, chemical, or biological factors (Saleem et al., 2020; Adetunji et al., 2020) ^[37, 19, 37, 19]. In fact, Saleem et al.(2020) ^[37]

revealed that the increased root growth of CCs may bring soil benefits, such as increased nutrient availability, elevated SOC levels, and improved soil aggregation. Furthermore, CCs have been demonstrated to facilitate nutrient cycling, the soil's features soil insect control, and weed suppression. CCs conserve θ for subsequent crops by reducing water soil evaporation, as per Sharma et al. (2018) ^[38]. In specific circumstances, this phenomenon has been observed. In the absence of irrigation, CCs frequently limit θ for future crops in water-limited conditions, as demonstrated by Basche et al. (2016) ^[39] (Nielsen et al., 2015a; Nielsen et al., 2015b) ^[40, 103].

Enhancing soil physical characteristics is crucial for soil conservation. CCs may enhance physical characteristics and SOM, hence mitigating soil erosion and improving SP and environmental quality. The article reviews the advantages of CCs for enhancing soil physical and hydraulic qualities, along with potential soil conservation benefits. The review demonstrates that CCs diminish ρ_b by around 4%, augment macropore volume by about 33%, and enhance I by up to 629% relative to soil without

CCs. These enhancements have been shown to result in a decrease in soil loss by up to 96% (Haruna *et al.*, 2020) [41].

Numerous research have established the impact of CCs on agricultural systems (Mukumbareza *et al.*, 2015; Coombs *et al.*, 2017) [43, 42]. The benefits may include enhancements in soil properties, improved soil chemical properties, biological features, and other benefits, such as reduced production costs. The soil water table (WT) has been significantly enhanced and θ has been significantly increased in a variety of soils that have been modified with CCs, such as hairy vetch and rye (Qi and Helmers, 2010) [44]. CCs help the following crops to access θ , stop soil evaporation, retain soil water and irrigation water, and reduce the kinetic energy (kE) of the falling rain drops to the soil surface (Sharma *et al.* 2018) [38]. In addition, CCs diminish wind erosion and the process of precipitation as well as the emission of particulate matter caused by wind and machine operations (Blanco-Canqui *et al.*, 2011) [24]. CCs can be used to control weeds by competing for light, water and nutrients, and/or by producing chemicals that affect other plants (Masilionyte *et al.*, 2017) [45]. CCs also increase the sequestration of carbon, soil stability in aggregates, and control of insects – all beneficial (O'Reilly *et al.*, 2011) [46].

CCs and soil fertility Evaluation (SFE)

CCs can alter soil properties by enhancing the availability of soil nutrients for current crops by increasing soil Organic Matter (SOM) combined with a high C:N ratio (Hubbard *et al.*, 2013) [47]. CCs increase available N via biological N fixation and also are able to retain excess soil N for subsequent planting season (O'Reilly *et al.*, 2012) [48]. The benefits of CCs are that they can reduce atmospheric CO₂ and N₂O emissions and increase C and N in soil (Fageria *et al.* 2005) [6]. When used with conservation tillage, CCs can increase SQ and CP (Schomberg *et al.*, 2009) [49]. CCs can also be able to fix nitrogen in the air, sequester carbon in the soil and limit weed growth (Möller *et al.*, 2008) [50]. In contrast to non-leguminous CCs, it is anticipated that leguminous CCs will incorporate between 60 and 80 kg ha⁻¹ of N into the soil. Non-leguminous CCs may also absorb surplus soil N, thereby reducing nitrogen loss (Fisk *et al.*, 2001) [51]. In comparison to the no-CCs (NCC) group, the use of an annual medic or clover CCs in no-till maize led to a 41-81% reduction in winter annual weeds. The incorporation of OM into the soil by CCs may enhance SQ by reducing compaction, increasing I, reducing water and nutrient runoff, and diminishing non-point-source contamination (Wyland *et al.*, 1996) [52]. It was determined that the leaching of nitrate (NO₃⁻) was reduced by 65-70% when CCs were substituted for winter waste. Soil loss caused by impact separation is prevented by CCs through the reduction of kE (Haramoto and Gallandt, 2005) [53].

The solitary CCs are unable to offer all of these benefits. However, the acquisition of a fleet of CCs could be highly advantageous from both an agricultural and environmental standpoint. Alfalfa, Austrian winter pea, hairy vetch, sunn hemp, and subterranean clover are among the most frequently employed leguminous cover crops by farmers and researchers. Further details are accessible through this link. The most frequently used grass cover crops are sudan grass (*Sorghum × drummondii*), annual ryegrass (*Lolium multiflorum* Lam.), oats (*Avena sativa* L.), and cereal rye (*Secale cereale* L.). Brassicas, buckwheat (*Fagopyrum esculentum* Moench), and summer or cool-season annual foliage cereals are additional examples (Teasdale *et al.*, 2007) [54]. SOC is crucial for the enhancement of environmental sustainability and CP. Reports suggest that SOC improves microbial activity and homogenizing the soil within the soil

ecosystem (Zhu *et al.*, 2019) [55], as well as impacts the supply of water (Drenovsky *et al.*, 2004) [56], accessibility to nutrients (Weintraub *et al.*, 2007) [57], and CP (Nkongolo and Haruna, 2015) [58]. The accumulation of SOC leads to an increase in C sequestration, which in turn enhances environmental sustainability (West and Marland, 2003) [59].

Some strategies of soil sustainability and their interaction with CCs

• Incorporation of CCs into Crop Rotation Cycles

An effective approach to mitigate erosion of soil and properly oversee soil and its nutrients for improved production is to integrate CCs into crop rotation cycles. CCs are cultivated for their numerous benefits, including their ability to protect the soil from water and wind erosion (Dabney *et al.*, 2001) [60]. Covering the soil with both live CCs and their residuals reduces transpiration and aids in maintaining the conservation of θ . CCs may diminish the development of surface seals, thereby enhancing soil water movement and decreasing runoff (Ruan *et al.*, 2001) [61]. Additionally, n can be improved by creating bio-pores and increasing earthworm activity (Lal *et al.*, 1991) [62]. CCs have been shown to enhance soil physical characteristics by diminishing ρ_b (Blanco-Canqui *et al.*, 2011; Haruna *et al.*, 2018a) [24, 62], improving SOC and aggregate (Steenwerth and Belina, 2008) [26], increasing macropores (Cercioglu *et al.*, 2018) [65], developing a θ (Basche *et al.*, 2016) [39], saturated conductivity indices of water (*Ksat*) (Yu *et al.*, 2016) [66], and I (Haruna *et al.*, 2018b) [66], and limiting soil loss.

• Incorporation of CCs into Tillage Systems

Adding CCs may enhance no-till work by altering the appearance and texture of the soil. Sunn hemp (*Crotalaria juncea* L.) boosted total I three times more than non-CCs plots and decreased near-surface ρ_b by 4%. Without N, sunn hemp and late-maturing soybean [*Glycine max* (L.) Merr.] reduced soil compactibility by 5% (Proctor maximum ρ_b). The reduction indicated that soils beneath CCs were less prone to getting compacted. In the 0-7.5 cm depth range, CCs also increase the average weight thickness of sediments by 80%. This research showed that between 0 and 7.5 cm of depth, late-maturing soybeans had 20% more SOC, and sunn hemp had 30% more than plots without CCs (Blanco-Canqui *et al.*, 2011) [24].

• Incorporation of CCs into soil mulching

Intercropping is the most effective management strategy for integrating CCs into a system of cropping to improve BP. When combined with primary crops, CCs serve as living mulches, allowing farmers to cultivate CCs without compromising acreage for the manufacturing of predominant crops (Afshar *et al.*, 2018; Alonso-Ayuso *et al.*, 2020) [68, 69]. Intercropping is the process of producing two or more crop species concurrently within a particular area throughout the growing season (Brooker *et al.*, 2015) [70]. Secondary crops, such as leguminous cover crops, are typically shorter plants that use scattered sunlight to grow alongside the main crop, like organic winter wheat, in relay intercropping systems. Through effective light resource partitioning made possible by this process, the major crop receives direct sunlight while the secondary crops rely on indirect light, increasing resource availability and the agricultural system's overall performance (Amossé *et al.*, 2013) [71]. Adopting the practice of intercropping led to better use of resources more efficiently (Morris and Garrity, 1993) [72]. All studies on intercropping

are based on the idea that resource use is best when different types of crops are grown together instead of just one type. Managing differences in how the species uses growing resources or acts in the environment where it is grown leads to that optimization.

Therefore, the successful operation of intercropping systems is crucial for the efficiency in farming practices, since the crops compete for the essential resources such as light, water and nutrients, which can affect their growth and CP. Weed control is also difficult as the number of chemicals is limited, and may be affected by crop interactions, which may cause disruption in field operations and reduce CP if not managed properly (Gitari *et al.* 2020) ^[73]. Intercropping might be considered unprofitable and/or uneconomical by farmers. Hence, theory and practice have to be combined to create efficient management strategies that maximize resource use efficiency in CCS intercropping system.

The literature on how to maximize resource use through intercropping has been directed towards management strategies such as interspecific connections, such as competition and facilitation (Hu *et al.*, 2016) ^[101]. Balanced crop combination of intercropping certain crops like safflower and bitter vetch in certain combinations as per research has been found to increase BPE and land use efficiency by reducing inter species competition and use of common resources. However, mixtures of mustard and legumes such as peas, lentils or chickpeas can result in significant reductions in individual CP and choosing appropriate intercropping patterns is essential to maximize productivity and sustainability (Banik *et al.*, 2000) ^[75]. The results indicate that the use of resources in intercropping cereals and legumes is superior to monocropping as the crops have a better interaction with each other. But if they are to be productive, they must be managed in a manner that observes some fundamental natural principles of efficient use of resources.

The efficacy of component crops in resource competition is quantified by intercropping indices. Nevertheless, BP data from intercropping CCs are rarely used to analyze these variables because the majority of research focuses on CP. As a result, a wealth of information on intercropping indices for intercrop systems is available, which may be used to evaluate the comparability of CPs (Banik *et al.*, 2000; Gitari *et al.*, 2020; Iqbal *et al.*, 2019) ^[75, 73, 76]. This data can be used to optimize BP by intercropping CCs using a number of management options. Relay intercropping allows for the deferral of cover crop planting, increasing crop dominance and reducing resource restrictions (Amossé *et al.*, 2013; Brooker *et al.*, 2020; Mhlanga *et al.*, 2016) ^[71, 77, 78]. Setting up dominant crop growth prior to planting CCs will improve their access to growth resources. On the other side, the main crop has an advantage in terms of timing, which hampers CCs' growth and development (Belfry and Van Eerd, 2016) ^[79] (Mhlanga *et al.*, 2016) ^[78] showed that planting CCs between growing corn could slow their growth and not really improve the CP of the intercropping plants. Research demonstrates that intercropping potatoes with legumes, such as climbing beans and similar species (dolichos), can boost land-use efficiency and SP through the application of diverse analytical tools to evaluate agricultural system performance. Evidence suggests that these systems offer a viable strategy for intensifying production, particularly for smallholder farmers, by optimizing resource use and promoting sustainable agriculture (Gitari *et al.*, 2020) ^[73].

After discussing the aforementioned points, one may be curious about the concepts of soil mulching, cover crops, and intercropping. In brief:

1. Soil mulching: These can be either natural, such as plant residues and rocks, or artificial, like petroleum-based

products or agricultural plastic used to cover the soil surface.

2. Plants known as "cover crops" grow to cover the soil's surface, preventing it from exposure and easy erosion. CCs crops do not include any CCy.

3. Intercropping: This involves planting two types of crops, either economic or non-economic, in the same field. For instance, you can plant different crops between rows.

● Incorporation of CCs into Soil water content (θ)

Living mulches can have a big effect on the link between soil and water, but the amount depends on the species, the farming system, the temperature, and the type of soil. Most agronomists now concur that understory plants play a crucial role in farming systems, preventing soil loss due to v. By putting CCs between rows of an economic crop, you can make the agroecosystem more diverse. These results show that intercropping potatoes and legumes may be a beneficial way to increase CP, especially for small-scale farmers (Baldé *et al.*, 2011) ^[80]. Usually, conventional ploughing methods leave open soil between rows of crops. This makes the soil less solid, more likely to be washed away by rain and wind, and it breaks down quickly. When raindrops hit the soil, they can wear away at bare soil. Still, the branches and leaves of CCs can cover the earth and keep most of the rain out, making rain splash less of a problem (Blanco-Canqui *et al.*, 2011) ^[24]. So, in live mulch systems, leftovers and understory plants can make v more difficult and slow it down, which is very important for stopping soil runoff.

Furthermore, rainwater that penetrates living mulch through absorption can help keep water in the soil and speed up the process of I. CCs make the earth less solid, more stable, and better at letting water in through the woody roots, which are made longer by the arbuscular mycorrhizal fungi system (Arruda *et al.*, 2021) ^[80], (Blanco-Canqui *et al.*, 2011) ^[24]. Living mulch soil cover keeps more water in the soil than bare soils, but the effect depends a lot on how much water the species of living mulch use (Liedgens *et al.*, 2004) ^[82].

Intercropping has demonstrated its ability to enhance CP from the same land area by making use of water that might otherwise be lost in monoculture systems to less efficient crops. However, soil type significantly influences its θ and the volume of water plant roots can extract across varying θ . In dryland farming, data comparing water use in intercropping systems with the water conserved by living cover crops is scarce. Some researchers suggest that the difference in water use between intercropping and monoculture systems during the growing season may be less than the weighted average (Morris & Garrity, 1993) ^[71, 72]. While intercropping systems generally require more water than monocultures, the actual amount depends heavily on climate and the selected crop species. As these systems can fulfill the water needs of high-yielding monocultures, they present valuable opportunities for agricultural development in water-scarce regions. Nevertheless, the water use of intercropping in dryland areas with rainwater harvesting (RWH) systems remains poorly understood. For instance, in waterlogged conditions, intercropping water consumption (ETc) surpasses the combined water use of individual crops. Due to water competition and complementary use during the growing season, intercropping ultimately consumes less water than the cumulative total of sole crops (Yin *et al.*, 2018) ^[82].

Scientific findings differ regarding the impact of living mulches on θ . Certain studies indicate that these mulches can compete with plants for water, leading to reduced θ in mulched areas compared to those without mulch (Qu *et al.*, 2019) ^[83, 84]. Live mulches have been demonstrated to increase soil moisture in other

investigations (Liedgens *et al.*, 2004; Ni *et al.*, 2016; Thorsted *et al.*, 2006) ^[82, 85, 86]. In the range of 0 to 5 centimeters, the soil moisture was increased by the living covering of turf grass, as observed by Ni *et al.* (2016) ^[85]. However, there was no effect on the soil moisture from 5 to 10 cm. In contrast, a separate investigation discovered that transpiration caused water competition at depths of 10-20 cm and 20-40 cm in living mulches (Qu *et al.*, 2019) ^[84]. Living mulches in wheat systems led to an increase in water evaporation from the soil surface (Thorsted *et al.*, 2006) ^[86]. In the same vein, the water content of the soil was decreased at depths of 30-90 cm when Italian ryegrass mulch was used in comparison to exposed soil (Liedgens *et al.*, 2004) ^[82]. Research shows that maize cultivated as a sole crop retains higher

transpirable soil water than systems with living mulches, suggesting improved θ utilization in mulch systems (Baldé *et al.*, 2011) ^[80]. However, other studies indicate CCs have no effect on θ (Nielsen *et al.*, 2015a; Payero *et al.*, 2021) ^[40, 87]. For example, cotton grown with single or mixed CCs under high rainfall (1400 mm) showed no changes in soil moisture (Payero *et al.*, 2021) ^[87]. Similarly, corn intercropped with Kura clover exhibited soil moisture levels comparable to pure Kura clover stands (Zemenchik *et al.*, 2000) ^[88]. Live CCs may reduce soil water via uptake and evaporation (Blanco-Canqui *et al.*, 2011) ^[24], though these effects are less noticeable during seasons with normal or above-average rainfall (Wortman *et al.*, 2012) ^[89].

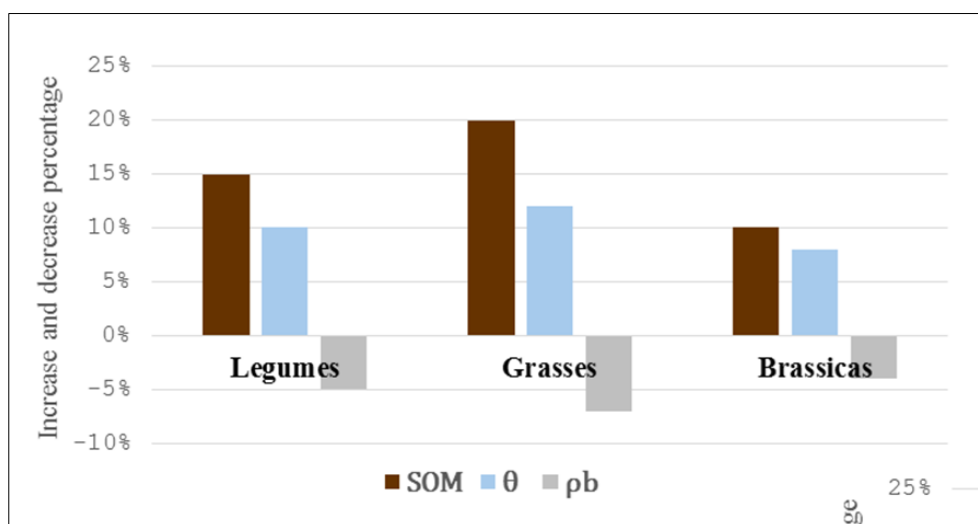


Fig 1: Descriptive effect of some types of CCs (Legumes, Grasses, and Brassicas) on θ , SOM, and pb

Table 1: Descriptive effect of some types of CCs (Legumes, Grasses, and Brassicas) on θ , SOM, and pb

Crop	Common effect in studies on: SOM, θ , and pb
Legumes	SOM and θ increase moderately, and pb decreases slightly.
Grasses	SOM and θ increase significantly, and pb decreases further.
Brassicas	exhibit a slightly lesser effect compared to grasses, yet they are effective in enhancing θ and SOM.

Conclusions

- CCs haven't been widely accepted by farmers, even though they have positive effects on many agroecosystem services (Mendes *et al.*, 2013) ^[90].
- Research indicates that inadequate CCs management can negatively impact CCy by competing for water and nutrients, potentially leading to disease spread or inhibiting seed development (Stipešević & Kladivko, 2005) ^[91]. Some factors that might deter the use of CCs to improve soil and protect wildlife include the direct and indirect costs of seeds, cultivation, and management, as well as the risk of animal grazing during winter (especially in small-scale farming) and potential economic losses (Snapp *et al.*, 2005) ^[10]. Several studies, however, have shown that the benefits of CCs outweigh their drawbacks (Miguez & Bollero, 2005) ^[92].
- Soil moisture (θ):** As CCs grow, they can help the earth dry out and get warmer in the spring. This may make farming easier but hinder plant growth. When it rains a lot in the winter, CCs growth can help get rid of extra water. Deep-rooted CCs such as fodder radish, plantain, and stubble turnips enhance I into the soil by three times. But if it's a dry year, the CCs may take away water from the crops below, making less water available for them. To maximize θ , consider soil type, rain, and CCs.

- Tillage and bulk density (ρb):** CCs can improve SQ and no-till performance, as shown in sunn hemp plots. They reduced near-surface ρb and I by 4%, while nutrient-free sunn hemp and late-maturing soybean reduced compatibility by 5%. CCs also increased aggregate mean weight diameter by 80% in the 0-7.5-cm layer, while sunn hemp and soybean plots had higher SOC (Blanco-Canqui *et al.*, 2011) ^[24].
- Soil organic matter (SOM):** It can be challenging to tell how CCs change the total amount of OM in the soil, especially in short-term tests and when the CCs aren't very productive. Several studies have found that SOM has stayed the same, while others have found rises ranging from 0.3% to 42% (compared to no CCs). It's important to note that no studies have shown that using CCs lowers the amount of SOM. SOM is more likely to rise in places where crops were killed later, when they had more stems and deeper, thicker roots. Low C: N crops break down faster and don't change the SOM as much over time. When CCs are well-established, they can contribute 1-3 t ha⁻¹ of OM, which is lower than the 4-5 t ha⁻¹ typically provided by most organic manures. However, organic manures, particularly compost, are more effective at retaining carbon (C) in the soil compared to CCs.

Finally, based on the previous three conclusions, the results of this

study demonstrate that the different types of CCs have different impacts on important soil attributes such as θ , SOM and pb as described earlier. To summarize these results, a descriptive graph (Figure 1) and tabulated data (Table 2) is provided for clarity only, and to give an approximate illustration of the differential effects of CC on these soil properties. This graphical and tabular output summarizes the relationships that they observed, and will be a summary of the entire study before presenting recommendations. Moreover, the increase or decrease percentages of these properties can be compared with the results of previous studies, which are mentioned below:

- **Increased SOM:** According to several studies, such as (Schmidt *et al.*, 2018; Steenwerth & Belina, 2008; Zemenchik *et al.*, 2000) [13, 26, 88], CCs, especially grasses and legumes, contribute to an increase in SOM of 10- 40% compared to non-CCs.
- **Increased θ :** Previous studies indicate that CCs improve θ by 5-15% in rain-fed or no-till farming systems (Basche *et al.*, 2016; Haruna *et al.*, 2020; Qi & Helmers, 2010) [39, 41, 44].
- **Decreased pb :** As reported in (Blanco-Canqui *et al.*, 2011; Nascente *et al.*, 2015; Haruna *et al.*, 2018a) [24, 28, 62], pb decreases by 4-7% after applying CCs, especially grasses.
- **Diversity of Benefits:** CCs have been found to have positive effects in numerous studies; however, these effects are subject to significant variation based on the soil type, elevation, and weather conditions during the CCs' growth phase (Poeplau & Don, 2015) [93]. CCs are typically cultivated in winter in moist temperate continental and subtropical regions, when the climate is cooler and potentially drier than during the primary crop growing season. Establishing CCs after the primary crop is a difficult task in regions that are semi-arid and where water is scarce and droughts are frequent during non-growing seasons (Idowu & Grover, 2014) [94]. For instance, Holman *et al.* (2012) [95] found that the viability of CCs in semi-arid low SOM pb southwestern Kansas, USA, was significantly influenced by the selection of species and the implementation of management strategies that were specifically designed for dry environments. In order to improve sustainability under both conventional and organic management, farmers worldwide are incorporating CCs into a variety of agricultural systems (Clay *et al.*, 2020) [96].
- **Economic Benefit:** The growing interest from researchers and funders has led to research on the benefits and uptake of CCs. Kladienko *et al.* (2014) [97] report that in Ohio, Indiana, Illinois, Iowa and Minnesota, 34-81% of fields were in CCs because of increasing awareness of benefits for soil health. The economic and agronomic benefits of CCs can increase soil productivity which in turn increases the likelihood of adoption by farmers (Arbuckle & Roesch-McNally, 2015) [102]. The mechanisms that underlie the benefits of CCs have not been fully understood, and there have been mixed or conflicting findings in many studies (Haruna *et al.*, 2020) [41]. Soil fertility and physical evaluations must be made with the most stable and least changeable properties such as soil pH and soil texture. These properties give an unambiguous idea about the identity of the soil and can be used to make an initial simplified decision. Long-term effects from the CCs on the properties should also be taken into account, because they can also have a significant effect on the pH and soil texture over the long term. Since soil texture is very hard to change and changes may not happen for hundreds or thousands of years, the properties of pb and structure become very important in determining other physical properties. These characteristics have an important impact on changes in

a, θ , and rpD , which in turn impact changes in overall SH and SP.

Some Concepts for Future Studies

• The possibility of Incorporation of CCs into Soil amendments

Applying CCs along with soil amendments is a powerful strategy to enhance SH and CP. Here are some key points on how to effectively integrate CCs with soil amendments:

1. **The selection of CCs:** The choice of CCs depends upon your soil type, climate and primary crop needs. Legumes are often used, such as clover and vetch, but grasses like rye and oats and brassicas like radish and mustard are also used.
2. **Timing:** Plant CC in off-season/as intercropping with main crops. This will give a sustained ground cover and maximise benefits.
3. **Incorporation Methods:** Once the CCs have developed, they can be incorporated into the soil by techniques such as mowing, rolling, or tilling. This helps in adding OM and nutrients to the soil.
4. **Soil Amendments:** Mix CCs and use an organic amendment like compost, manure or biochar. The amendments help to create a more favourable soil structure and provide more nutrients for the soil along with boosting microbial activity.
5. **Monitoring and Management:** Regularly monitor SH indicators such as pH, nutrient levels, and OM. Fine-tune cover crop and amendment plans according to the outcomes.
6. **Benefits:** CCs and soil amendments may increase soil fertility, soil θ , and decrease erosion and increase CP.

The possibility of compensating for ploughing and its adverse effects by planting CCs, which contributes to improving the properties of the soil that the ploughing works on.

Recommendations for Practice

To effectively integrate CCs into agricultural systems and maximize their benefits for soil fertility and physical properties, the following practical recommendations are proposed:

1. **Cover Crop Selection:** Select CCs according to regional climate and soil type and main crop requirements. Drought-tolerant species such as sorghum-sudangrass, vetch or sunn hemp are suggested in dry and semi-arid areas, because they have the ability of biomass production and root development.
2. **Planting Time:** To minimize land competition, plant CC during the off-season or inter-row during the main crop growth cycle. Planting in dry climates should take place immediately after rain or irrigation to aid germination.
3. **Termination Strategies:** End CC before they become a serious competitor for main crop for nutrients and water. In an organic system, mechanical termination (rolling or mowing) is preferred and in a conventional system, chemical termination can be used.
4. **Soil Monitoring:** Regularly monitor key soil indicators such as θ , pb , SOM, and pH to evaluate the effectiveness of CCs and adapt practices accordingly.
5. **Integration with Other Practices:** Use CCs in combination with conservation tillage, organic amendments or intercropping systems to increase SH, improve I and decrease erosion.
6. **Farmer Education and Support:** Train, demonstrate and make available extension services to farmers to have the correct implementation and maintenance of CCs.
7. **Economic Considerations:** Evaluate the cost-benefit ratio of CCs. While initial costs may be high (seeds, labor), long-term gains in SH, CP stability, and reduced input requirements

often outweigh these investments.

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