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The Role of Cover Crops towards Sustainable Soil Health and Agriculture—A Review Paper

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Abstract

Cover crops are the plants which are grown to improve soil fertility, prevent soil erosion, enrichment and protection of soil, and enhance nutrient and water availability, and quality of soil. Cover crops provide several benefits to soils used for agriculture production. Cover crops are helpful in increasing and sustaining microbial biodiversity in soils. We summarized the effect of several cover crops in soil properties such as soil moisture content, soil microbial activities, soil carbon sequestration, nitrate leaching, soil water, and soil health. Selection of cover crops usually depends on the primary benefits which are provided by cover crops. Other factors may also include weather conditions, time of sowing, either legume or non-legume and timing and method of killing of a cover crop. In recent times, cover crops are also used for mitigating climate change, suppressing weeds in crops and increasing exchangeable nutrients such as Mg^{2+} and K^{+}. Cover crops are also found to be economical in long-term experiment studies. Although some limitations always come with several benefits. Cover crops have some problems including the method of killing, host for pathogens, regeneration, and not immediate benefits of using them. Despite the few limitations, cover crops improve the overall health of the soil and provide a sustainable environment for the main crops.

Keywords

Cover Crops, Sustainable Agriculture, Soil Health, Legumes, Soil Properties

1. Introduction

Cover crops are defined as the crops which are used to cover the ground surface. These crops are precisely grown to protect the soil from erosion and prevent loss of nutrients in deep layers through leaching and surface runoff [1] [2]. Cover crops are planted between main crops to improve agriculture production and productivity. Basically, cover crops revolve around legumes which are cultivated to cover the surface of the soil and helpful in improving physical, chemical and biological soil properties. Ideal cover crops should germinate and emerge quickly, be tolerant to adverse climatic conditions, be able to fix atmospheric nitrogen from the air, absorb nutrients from soil by developing deep roots, produce higher amount of biomass in shorter period, be easy to work and cultivate, not compete with main crop, be tolerant to insect-pest and diseases, have ability to suppress weeds, and be cost-effective for cultivation [3]. Cover crops have been well known for decades defining the benefits for the environment and farming community [2] [4] [5]. No tillage system (NTS) [6] is a soil management technique that increases soil organic matter [7] accumulation, reduces soil disturbance and can increase crop yield [4]. The SOM can be increased by growing cover crops under an NTS [8]. Approximately half of the agriculture area in Brazil has practiced no tillage system [9]. Interest is growing in using cover crops to improve crop production and soil quality in worldwide including Brazil [10].

Mycorrhizal fungal activity in improving soil quality has been widely accepted. Cover crops help to increase mycorrhizal fungi inoculation in soil [11]. Mycorrhizal fungi also help in enhancing early crop growth and survival of crops, especially in cotton. It forms symbiotic relationships with plant roots which can assist nutrient and water uptake [12]. Early growth and higher yield of cotton were observed after the wheat cover crop was correlated with early root infection with mycorrhizal fungi. It was found that cotton roots beneficially engage with existing mycorrhizal fungi that developed an association with the root system of the wheat cover crop [13]. Cover crops terminated at an early stage may lack mycorrhizal fungi. This was observed in wheat cover crop terminated at 4 to 6 weeks age, which had no impact on growth or yield of successive soybean crop [14]. When rye was left as surface mulch after removing its aboveground parts in a conservation tillage system, it results in keeping the soil wetter and increase crop yield [15]. It was reported that rye as cover crop resulted in higher biomass compared with other species and soil had more water content under rye [16]. Mulched and bare soils can show the great difference in water content during short dry periods (1 - 2 weeks) [17]. Cover crops can be managed as mulches by terminating their growth using paraquat (N,N'-dimethyl-4,4'-bipyridinium dichloride), glyphosate (N-(phosphonomethyl) glycine) [18] or a mixture of pre-emergence, non-selective and post-emergence herbicides [6].

Usually, non-chemical methods of suppressing or killing of cover crops are preferred by growers to reduce the use of chemical inputs. These methods may include rolling, mowing, undercutting, partial roto tilling and roll chopping [19].

insect-pest and diseases. Cover crops can be used as leguminous or non-leguminous. Legume cover crops are used to fix atmospheric nitrogen which is used by succeeding crop [17], although non-legume cover crops are chiefly used to reduce soil erosion and nitrate leaching [20]. Nitrogen fixation by legumes helps to reduce the use of nitrogen fertilizers for next crop [21]. The non-leguminous cover crops are the plants that are grown to provide soil cover and help to improve physical, chemical and biological characteristics of the soil. Green manures application to soil helps to improve organic matter, fertility status [22] and raise nutrient holding ability of soil [23]. Non-legume cover crops also help to reduce nitrogen leaching from the soil profile [20] [24]. Biomass produced by 45 days old pearl millet used as cover crop helps to improve the yield in succeeding baby corn crop [25]. A bicultural of legume and non-legume can be used with the objective to provide both benefits together [26]. Hence, the objective of this paper is to summarize the role of cover crops to improve the agricultural soil conditions for sustainable agriculture. This review emphasis on role of cover crops in improving soil health by controlling soil erosion, preserving soil moisture, controlling weed growth, helping in carbon sequestration, improving soil and water quality, controlling insect and pest population, and providing economic benefits.

2. Ecosystem Parameters

2.1. Soil Erosion

Cover crops are basically sown for the controlling of soil erosion [27]. These are the effective tools to control erosion and technique to conserve the environment. The importance of cover crop for controlling soil erosion is illustrated by the pioneer work done at Belgium with the different cover crops including white mustard (*Sinapis alba*), Phacelia (*Phacelia tanacetifoli*), Oats (*Avena sativa*), ryegrass (*Lolium perenne*), Fodder radish (*Raphanus sativus subsp. oleiferus*). Results indicated that cover crops have root density ranges from 1.02 for phacelia and 2.95 kg m^{-3} for ryegrass. Crop species with fibrous root system (e.g. ryegrass, rye and oats) show high potential to control soil erosion while cover crops with thick roots (e.g. white mustard and fodder radish) are less effective in preventing soil erosion [28].

2.2. Soil Moisture Content

It was found that use of cereal rye (*Secale cereale* L.) as cover crop helped to improve soil water in maize-soybean cropping system [29]. Similarly, another study conducted for 7 years by successive use of winter rye as cover crop in maize-soybean cropping system found to be effective in conserving soil moisture and improving soil water table. Cover crops help to reduce evaporation from the soil surface, conserves moisture from the irrigation and rainfall, and help in soil moisture availability to the subsequent crops. Cover crops increased water retention in soil at water potentials related to field capacity and plant available water by 10% - 11% and 21% - 22%, respectively [30].

Winter annual rye cover crop helps to increase water at field capacity [31] and hence winter annual rye and hairy vetch increase available plant water content [32]. Cover crops act as a hindrance between the soil surface and precipitation especially rainfall, it enables to reduce the rainfall intensity that falls on the ground. Water drops slowly trickle down into the ground through soil pores, which are formed by soil macro fauna enhanced by cover crop root growth. Thus water infiltration increases in place of draining off results in recharging soil water storage [33] [34] [35] [36]. Another study conducted at the university of California reported that cover crops including brome grass, resident vegetation, and strawberry clover enable to reduce surface soil strength by 38 to 41 percent, also increased soil infiltration rate by 37 to 41 percent and cumulative water uptake by 20 - 101 percent [37].

2.3. Weed Management

Crop weeds are among the major agronomic problems in intensive farming system mainly in the organic farming system. Use of chemicals is more effective as compare to non-chemical methods of weed control [38]. Damage caused by weeds mainly depends on biological properties of crop plants, environmental conditions and soil surface cover intensity [39] A field experiment was conducted at Lithuanian Research Center for Agriculture and Forestry from 2006-2012 to investigate the competitive ability of plants grown as cover crops. These cover crops include narrow-leafed lupine (*Lupine angustifolius* L.) with mixture of oil radish (*Raphanus sativus*), white mustard (*Sinapis alba* L.) and white mustard with a mixture of common buckwheat (*Fagopyrum exculentum* Moench) for smothering weeds in organic and sustainable farming systems in soils having low humus (1.90% - 2.01%) and moderate humus (2.10% - 2.40%) content. It was revealed that white mustard cultivated as a sole crop or in combination with buckwheat is more effective for weed smothering as compared to narrow-leaf lupine grown in mixture with oil radish in the organic farming system. Field plot grown without cover crops in both low and high humus content soils were observed for large number and biomass of weeds in comparison to plots grown with cover crops. Results demonstrated that white mustard and mixture of white mustard with buckwheat were most effective for inhibiting volunteer plants and weed biomass in soils having low and high humus content. This experiment showed that cover crops have competitive ability to control weed growth, and can be used as weed control tool in crops [40].

2.4. Soil Carbon Sequestration

Cover crops potential to increase soil organic carbon (SOC) has been discussed in limited studies [41]. Agricultural soils are depleted in SOC as compared to soils under natural vegetation cover. Crop cultivation leads to SOC losses of 30 to 40% in comparison to natural vegetation [42] [43]. SOC sequestrated in conventional tillage and no-till soils can be influenced by different crop management practices due to the difference in plant carbon inputs and rate of mineralization. An experiment conducted at Fort Valley State University found that SOC at 0 - 10 cm fluctuated with plant carbon input and was greater from the cover crops (hairy vetch, rye, mixture of hairy vetch and rye) as compared to no cover crops (weeds) in cotton (*Gossipium hirsutum* L.) and Sorghum (*Sorghum bicolor* L.). The SOC at 0 - 30 cm depth was increased to 120 - 130 kg N ha^{-1} yr^{-1} in cover crops treatment in comparison to 0 kg N ha^{-1} yr^{-1} in no cover crop treatment [44]. Field study performed at Germany overlooked the effect of cover crops on SOC. Cover crops have an advantage over the other management practices that increased SOC does not decrease the yield of the main crop. Meta-analysis was conducted from 139 plots at 37 different sites to evaluate carbon response function describing SOC changes as a function of time. Cover crops in rotation observed up to 54 years was linearly correlated in soil depth of 22 cm with annual SOC change at the rate of 0.32 ± 0.08 Mg ha^{-1} yr^{-1} (R^2 = 0.19). Average SOC stock change was modeled with the assumption that observed linear SOC accumulation will not increase indefinitely. The newly predicted steady state data after using cover crops for 155 years would have SOC accumulation of 16.7 ± 1.5 Mg ha^{-1} yr^{-1} [45].

2.5. Nitrate Leaching

Losses through nitrate leaching in conventional grain-production system range between 10% to 30% of applied nitrogen. It is a complex process which depends on climate variables, characteristics of soil and management practices [46] [47]. Leaching of nitrate is a major concern due to its direct effect on drinking water, eutrophication of sea water and to increase atmospheric pollution with ammonia. Soil management practices including precision agriculture can be helpful to mitigate nitrogen leaching in agricultural soils [48]. Another important study demonstrated that nitrogen in agricultural soils can be efficiently managed using green manures and cover crops [49]. Cover crops have an ability to decrease nutrient requirement particularly nitrogen for the subsequent crop; nitrogen is captured by roots, prohibits the nitrate leaching into groundwater and prohibits downward movement into the soil profile [50]. An experiment conducted from 1992 to 1994 at Sweden to estimate the effect of perennial ryegrass (*Lolium perenne* L.) as a cover crop sown in barley (*hordeum vulgare* L.) on nitrate leaching and availability of nitrogen to the main crop. Results showed that cover crop reduced the concentration of nitrate leaching by less than 5 mg L^{-1} as compare to 10 - 18 mg L^{-1} without cover crop [51]. Oats (*Avena sativa* L.) and rye (*Secale cereale* L.) cover crops were evaluated in reducing nitrate concentrations. Oats reduced nitrate concentration by 26% whereas rye reduced 48% nitrate concentration [52].

2.6. Climate Change

Climate change mitigation addresses the approaches that reduce the anthropogenic climate system [53]. In agriculture system, various strategies to mitigate biogeochemical include reduction in greenhouse gas emissions, reduce nitrogen fertilizer production, increasing sink for greenhouse gases in soil [54]. Cover crops should be selected based on the climate conditions (**Table 1**). Nitrate leaching was 40% lower in legume cover crop treatment than fallow systems and 70% lower in non-legume cover crop treatment than fallow system [55]. Cover crops enable to mitigate warming through greenhouse gas flux by 100 - 150 g CO_2 e/m^2/year which is higher as compare to mitigation through no till. An estimation using case studies to calculate the change of surface albedo due to cover crops showed mitigation around 12 - 46 g CO_2 e/m^2/year over 100 year period. Cover crops management help to climate change adaption through reduction of erosion from rains, retention in mineralized nitrogen due to warming, and increases soil water management options during soil saturation period or in droughts [2].

2.7. Earthworm Population

Rye (*Secale cereale* L.) planted in corn silage-soybean rotation results 1.2 times higher earthworm population and 1.4 times' higher biomass in cover crop plots compared to no cover crop plots. Long-term cover crop usage contributes to improving soil structure and increases earthworm population which subsequently reduces nutrient and sediment losses in surface runoff [56]. Cover crops such as pea and oat showed the evidence for higher earthworm populations compared to bare fallow plots in a or the cover crop-spring barley crop rotation. Brassica species such as mustard had large above ground biomass but less earthworm population [57].

2.8. Microbial Population

Cover crops are widely growing strategy to enhance soil microbial growth in agricultural systems. Conventional tillage [58] and No-tillage system (NT) with a ryegrass cover crop in cotton (*Gossipium hirsutum* L.) was studied for the microbial count and enzymes activities in soil. Ryegrass cover crop in CT and NT maintained a higher microbial population in the upper layer (2 cm) compare to no-cover plots; while CT soils had greater bacterial and fungi colony-forming

Table 1. Some basic parameters to choose the cover crops.

Parameters		Crops	Primary benefits	References
Weather conditions	Winter cover crops	Winter rye, brassicas, hairy vetch, red clover, oats	Controls erosion, source of nitrogen fixation, soil organic matter, improves soil structure	[82]
	Summer cover crops	Buckwheat, sorghum Sudan grass, cowpea, sun hemp	Increase soil organic matter, enhance soil microbes, weed suppression, reduce soil erosion	[83] [84]
Type of cover crops	Legumes	Hairy vetch, peas, red clover, crimson clover, beans	Nitrogen fixation, prevent soil erosion, increase organic matter, helpful for insects and pollinators	[85]
	Non legumes	Wheat, oats, barley, annual ryegrass, brassicas, mustards, buckwheat	Prevent soil erosion, nutrient scavenging, weed suppression, provide ground cover	[85]

units (CFUs) in 2 to 10 cm depth. Cover crops under NT maintained hundred-fold higher CFUs than other treatments [59]. A field experiment was conducted in Pennsylvania to examine the effect of cover crops and their mixtures to understand microbial community structure and biological activity in soil. Results showed that individual cover crops (oats and cereal rye) favored Arbuscular mycorrhizal (AM) fungi whereas hairy vetch (*Vicia villosa* L.) as a cover crop was associated with non AM fungi. A Mixture of multiple species also found in cover crop-microbe association. This shows a clear relation between cover crops and microbial communities [60].

2.9. Pest Management

Cover crops nature to fight against pest help to reduce pesticides use and it is cost effective along with environment-friendly also. Cropping systems have cover crops beneficial in preserving natural resources, profitable and socially accepted [61]. *Sesbania exalanta* is used as warm-season cover crop under pecan orchards in southern Georgia to control aphidophagous coccinellidae and pecan aphids [62]. Annual ryegrass and cereal rye cover crops are found significant in reducing soybean cyst nematodes. Cover crops used as trap crop in corn are effective in controlling corn earworm and tarnish bugs. It also helps in reducing soil-borne pathogens in long-term studies [63]. Cover crops residue is buried in soil to reduce diseases and destroys the habitat for insects and control weeds [64]. An experiment conducted at Maine using barley, canola, rapeseed and ryegrass as full season crop rotation with potato; it enables to reduce Rhizoctonia by 15% to 50%. An addition of winter rye fall cover crop to these rotations further reduced Rhizoctonia and common scab diseases for another 5 to 20 percent [65].

2.10. Soil and Water Quality

Twenty-five years conventional tillage study shows that cover crops enable to increase soil permeability, soil organic matter, porosity (macro) and also cotton yield [66]. Winter cover crops such as oats and rye have the capacity to elevate soil organic carbon in corn-soybean production system [67]. Cover crops increase soil water content with the crop biomass and infiltration. However, it also involves decreasing water content through transpiration. Cover crops also help to decrease surface drainage and maintain soil quality [29]. Another study was conducted at Southern Illinois for 12 years using cover crops in no-tillage (NT), moldboard plow (MP) and chisel plow (CP) treatments in annual corn and soybean cropping system. All the treatments with and without cover crops have the same yield, but plots having cover crops resulted in higher soil organic carbon content as compared to without cover crops [68].

2.11. Wildlife and Biodiversity

Different cover crops are advantageous for accommodating beneficial insects, and at the same time control pest population. Several flowering cover crops including legumes, clovers or buckwheat are valuable for fascinating the insects and animals. Cover crops are also helpful to attract pollinators for improving the rate of pollination in crop field. Use of crimson clover as cover crop with non-Bt cotton encouraged natural control of bollworm (*Helicoverpa armigera*) and reduced use of pesticides. Predator's (*Geocoris punctipes*) population starts increasing on crimson clover in early spring season and consequently preyed on bollworm pests in early season cotton. Cover crops (crimson clover) also provide honeybees and nectar to pollinators. Also, use of conservation tillage in rye cover crop encouraged natural control of *Helicoverpa armigera* in non-Bt cotton, and in addition to this, minimized the use of insecticides. Use of rye cover crop in conservation tillage protects the habitat of fire ants and hence improves predation of *Helicoverpa armigera*, as fire ants are predators of eggs and larvae of *Helicoverpa armigera* in cotton [69] [70].

2.12. Economic Consideration

Literature having an economic assessment in relation to effects on returns, or fertilizer inputs is available, but limited information is available about the economic evaluation of cover crops related to benefits to soil [71]. The experiment conducted using cattle grazed and non-grazed winter rye as a cover crop in cotton had returns ranging from $26 - 355 with an average of $81/ha [72]. It was found that cover crops in a no-tillage system and minimum tillage would be $25.60/acre and $15.10/acre, respectively. It is suggested that cover crops may be beneficial in future as continuous use of cover crops improves soil organic carbon, physical properties and level of organic matter [73]. Economics of cover crops depend on the soil type, weather conditions, region and also the management practices. The economic impact of short-term adoption and long-term adoption of cover crops assessed using hairy vetch as a cover crop in cotton production in Northwest Louisiana. Categories accounting benefits for nutrient credits include the reduction in fertilizer purchase (N, P, and K), credit in erosion reduction, reduction in the purchase of herbicides and increase in yield of cash crop after cover crop. Long-term adoption of cover crops found to be benefit in soil fertility and soil water storage. An additional benefit for using long-term cover crops resulted by an increase of $13/acre/year as compared to short-term analysis. Overall, total net benefits found to be $1354/acre/year for adoption of long-term cover crops [74].

2.13. Overall Soil Health

Soil health has attracted the attention of researchers from last two decades, few studies are found regarding the effects of cover crops on the soil health and management (**Table 2**). An experiment was conducted in California with an objective to determine whether the impact of long-term no-tillage and cover crops, alone or in combination would improve physical properties. Several cover crops have effect on the soil chemical properties such as nutrient content, salinity or sodicity, soil organic carbon, and ion exchange capacity of soils (**Table 3**). It was observed in 15 years long experiment that properties such as soil aggregation, infiltration rate, soil nitrogen level, water extractable organic carbon, and biological activities of microbes were all increased by using no tillage and cover crop practices [75]. Residues of various crops help to return organic matter to the soil which is retained in soil through the combination of various physio-chemical and biological properties which in result maintains soil health and quality [76]. Studies showed that crop residues left in the field help to retain soil health. An experiment performed in Mexico for 6 years by leaving around 60% of crop residues after livestock feeding helps in soil carbon sequestration [77].

2.14. Selection of Cover Crops

Several benefits of cover crops have been discussed in all the above points. For selecting a cover crop, there is need to clarify the primary need for using a cover crop. Time of planting, a method of planting, time of killing the cover crops, a method of killing (either using machine or chemicals) need to be considered. It is necessary to make a plan for the primary purpose of cover crop (**Table 1**). For making a plan, we need to look at the crop rotation, type of soil, irrigation level and traits of a cover crop as well [78]. There is also a requirement to protect the environment and conserving natural resources. Researchers found that using cover rotations and cover crops are best management practices from ancient times [79].

Table 2. Effect of cover crops on soil physical properties.

Study Site	Study Year	Cover Crop	Main Crop	Effects	References
Coastal plain experiment station, GA	2002-2005	Sun hemp and Crimson clover	Corn	Increase soil C and N, decrease bulk density, increase saturated hydraulic conductivity	[86]
Lincoln university, MO	2011-2012	Cereal rye	Corn-soybean rotation	Bulk density decreased by 3.5%, C:N decreased	[87]
Hesston, KS	1995-2000	Hairy vetch, sun hemp	Winter wheat-grain sorghum	Increase soil organic carbon by 30%, increase infiltration rate, decrease bulk density	[88]
Central valley, California	1991	Broom grass, strawberry clover	-	Reduced soil surface strength by 38% - 41%, increase infiltration rate by 20% - 101%	[37]
Maryland	13 years	Hairy vetch	Corn	Increased aggregate stability, water infiltration	[89]

Table 3. Effect of cover crops on soil chemical properties.

Study Site	Study Year	Cover Crop	Main Crop	Effects	References
South Brazil	2012-2013	Rye, black oats, oilseed radish	Onion	Rye plant residues showed highest half-life, slowly release nutrients	[90]
Sudan Savannah, Africa	1986-1987	Pigeon pea, beans	Corn	Increase exchangeable K^+, Soil matric potential, C/N ratio, soil organic carbon	[91]
State of Mato Grosso do Sul, Brazil	2010-2014	Intercropping with several cover crops	Fall-winter maize	Results in high exchangeable Mg^{2+} and K^+, P content increase in 5 - 10 cm soil	[92]

2.15. Limitations of Cover Crops

Due to lack of knowledge, many farmers are not aware of cover crops. Few small farmers lack some machinery for planting or killing the cover crops mechanically. The requirement of labor, timeline of cover crop, limited machinery for the cover crops further make it hard for farmers to grow cover crops. Practicing cover crops would not produce the immediate beneficial results, so using cover crops in cropping system would increase initial cost, labor and machinery. Also, there are limited marketing facilities for using perennial crops such as alfalfa, red clover or orchard grass [80]. Cover crops could act as an alternate host for insects and pathogens in the offseason. Few species of insects and pathogens use the cover crop to complete their life cycle in the offseason and act as major pest for the main succeeding crop [81]. Using cover crops in the long-term cash crop rotations may not be compatible. Expenditures for new equipment for planting and terminating, management practices are also some of the limitations of cover crops [63]. Cover crops especially non-legumes (sorghum, pearl millet or corn) have the potential of re-emergence if these cover crops are not terminated properly. These re-emergence cover crops compete with the main crop for space, light, water and nutrients [25].

3. Conclusion

Our review suggests that cover crops have excessive ability to contribute to sustainable agriculture production. Cover crops improve the overall health of the soil by reducing soil erosion (water and wind erosion), providing better soil structural properties (aggregate stability), improving soil hydraulic properties (water infiltration), and by enhancing the SOC, soil microbial population, and reducing the nitrate N leaching and hence reduce the groundwater pollution. Cover crops help in climate change adaptation and mitigate greenhouse gas emissions. However, different benefits of using cover crops depend on the selection of species (legumes, non-legumes, grasses, and brassicas), timing of planting and termination of the crop, and methods of termination of cover crops (mechanical or chemical). For example, cover crop species which have fibrous root system are found to be more effective in controlling soil erosion as compared to tap root system. Few studies have also shown that when cover crops are grown in mixture with main crops, it competes with nutrient and water availability. Cover crops are generally beneficial after long-term use as findings indicate that the long-term use of cover crops have resulted in economical use. Researchers are focusing on other possible benefits which can be taken by using cover crops. There are a number of factors which need to study including allelopathy effect using cover crops, use of different mixtures of cover crops and their management strategies for improving soil health and quality.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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