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The Role of Cover Crops in Sustainable Agriculture: Benefits, Challenges, and Future Directions

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ABSTRACT

Cover crops provide several benefits, such as enhancing soil fertility, reducing weed pressure, improving water retention, and mitigating soil erosion. Several studies show they also play a vital role in carbon sequestration and mitigate climate change by reducing greenhouse gas emissions. In addition, the contribution to the long-term sustainability of regenerative agriculture systems is one significant role of cover crops. Though they offer multiple advantages, we face challenges like labor costs, managing complexity, and the need for tailored species selection based on environmental conditions. The paper helps to decipher the multiple benefits that cover crops offer, assesses the associated challenges, and discusses future directions for research and policy to build up their integration into modern agricultural practices. Also, studying the patterns of studies related to cover crops in the past decades helps us to understand previous outcomes and challenges. Documenting these challenges can be integral to regenerative agriculture systems that support long-term environmental sustainability and food security.

INTRODUCTION

Cover crops are growing densely to protect and enhance the soil during times when major crops are not being cultivated. In recent agricultural practices, it has played a vital role in improving soil properties and enhancing organic matter, reducing erosion, and managing nutrients.

Cover crops are "close-growing crops that provide soil protection, seeding protection, and soil improvement between periods of normal crop production, or between trees in orchards and vines in vineyards", according to the Soil Science Society of America. Cover crop use has a long history, dating back to ancient civilizations. For instance, in the "Three Sisters" method, Native Americans practiced this method where they grew corn, beans, and squash together. This method benefits both crops and soil health. Similarly, in early America, George Washington used clover, grass, and buckwheat in his crop rotations to restore soil nutrients (Groff, 2015). Nowadays, multiple conservation programs and policies promote their adoption, acknowledging their importance in the mitigation of climate change, boosting diversity, and enhancing farm resilience (Feng et al., 2024). For food and non-food crops like biofuel and textile (13%), 43% and 87% of the total global land area, except glacial and barren land, is used (Poore & Nemecek, 2018). In the current situation, having limited agricultural land, most countries have transitioned from an extensive to an intensive farming system (Diniz et al., 2013). Cover crops typically come up with climate benefits without compromising on-farm benefits, concluded to a meta-analysis conducted by the Berkeley Agroecology Lab. In the southeastern United States, A study revealed that crop-livestock systems can have positive aspects and serve as a key source of high-quality forages during the short period of cash crops, contributing to the sustainability of the farming system (Franzluebbers & Stuedemann, 2015).

MATERIALS AND METHODS

Secondary sources were used to collect the data. Different articles, journals, and internet sites were visited to gather the related information. From varied topics, information is recorded systematically.

RESULTS AND DISCUSSION

Cover crops are critical in addressing several global agricultural challenges, including soil degradation, climate change, and food security. Here is how they are linked:

Soil Degradation

Cover crops are crucial in reducing soil erosion and degradation by enhancing the soil's structure and organic matter content and promoting microbial activity. Also, they help to protect the soil from wind and water erosion by providing ground cover. In addition, through atmospheric nitrogen fixation and the capture of residual nutrients to make them available for subsequent crops, cover crops enhance soil fertility (Muluneh & Muluneh, 2021). There is compelling evidence that cover crops improve carbon storage in soil (M. D. M CDANIEL et al., 2014; Schipanski, Barbercheck, et al., 2014). However, there is a lot of significant variability between sites, and it is more noticeable when there is reduced tillage, multiple crop rotations, and high nitrogen inputs (Lal & Lal, 2015). Incorporating cover crops into annual crop rotations improves the ecosystem services that agricultural systems offer (Schipanski, et al., 2014).

Climate Change

According to the climate crisis, years of unsustainable farming in the United States have brought soil erosion, pollinator loss, and exposed farmworkers and livestock to extreme heat, and other harmful impacts. Likewise, the land is more vulnerable to climate change impacts like drought and extreme weather as they enhance the soil's ability to retain water. Though in 2019, about 10 percent of U.S. greenhouse gas emissions came from agriculture, sustainable agriculture practices, which include cover crops, agroforestry, no-till farming, sustainable livestock grazing, and soil amendments, help farmers mitigate and adapt to the climate crisis. In case of climate change, cover crops act as a buffer to contribute to both mitigation and adaptation via sequestration of carbon in the soil, therefore reducing greenhouse gas emissions. Cover crops enhance the soil's ability to retain water, which is crucial during periods of drought. They also help in reducing the need for synthetic fertilizers, which are significant sources of nitrous oxide, a potent greenhouse gas (Kaye et al., 2017).

Food Security: Cover crops are essential for maintaining food security because they enhance soil health, boost crop yields, and increase farm resilience. To have sustainable agriculture, they maintain soil fertility, minimize erosion, and improve water retention. To feed the world's expanding population, cover crops can result in higher and more consistent yields, which is essential (Quintarelli et al., 2022). Notably, with a potential yield increase of up to 24%, legume cover crops exhibited the highest potential yield gain (Scavo et al., 2022). For instance, research conducted in South Asia has shown that cover crops, which are comparable to plastic mulching, had the most rows per cob in corn. It might be an alternative option for those who cannot afford the cost of plastic (Sanwa et al., 2023b).

Because more people are aware of the agronomical and environmental advantages of cover crops, their use has seen a substantial rebound in recent decades. According to the USDA Census of Agriculture, cover crop use has increased from 10.3 million acres in 2012 to a projected 20 million acres in 2020 (Blanco & Lal, 2023). Additionally, several conservation laws and programs have provided financial and technical aid to farmers to encourage the use of cover crops.

Table 1. Different types of Cover crops

Type of Cover Crop	Examples	Benefits
Leguminous Cover Crops	Clover, Vetch, Cowpea, Field Pea, Hairy Vetch, Sweet Clover, Red Clover, White Clover	Nitrogen fixation, improved soil fertility
Grasses	Rye, Oats, Barley, Annual Ryegrass, Winter Wheat, Triticale	Erosion control, biomass production, improved soil structure
Brassicas	Radish, Mustard, Rapeseed, Turnip, Kale	Pest suppression, soil compaction reduction, enhanced nutrient cycling
Mixtures	Clover + Rye, Vetch + Oats, Radish + Rye, Pea + Barley	Combined benefits of nitrogen fixation, erosion control, and pest suppression

(Dean & Weil, 2009; Finney et al., 2016; Hartwig & Ammon, 2002; Sarrantonio, 2007)

Benefits of Cover Crops

1. Soil Health

The purpose of cover crops is to enhance and cover the soil. Both living and dead, they can be plowed into the ground (Benedict et al., 2014). Because cover crops increase organic matter in areas with high C: N ratios, they can change the characteristics of the soil and increase the nutrients available for subsequent crops (Hubbard et al., 2013). From the survey, reducing soil erosion and improving soil health are the two advantages of cover crops that users rank highest. According to both users and nonusers of cover crops, the main perceived barriers are the costs involved and the lack of knowledge (Golden et al., 2023). An integrated strategy involving a sustained dedication to using combinations of techniques that improve the biological, chemical, and physical properties of the soil is necessary for managing enhanced soil health. Increases in soil C and N levels, bulk density, saturated hydraulic conductivity, and soil moisture retention were all brought about by cover crops (Adetunji et al., 2020b). Legume cover crops did not affect bulk density. However, in comparison to a fallow system, no-tillage cotton grew more quickly when it was planted after common vetch or crimson clover (Touchton et al., 1984).

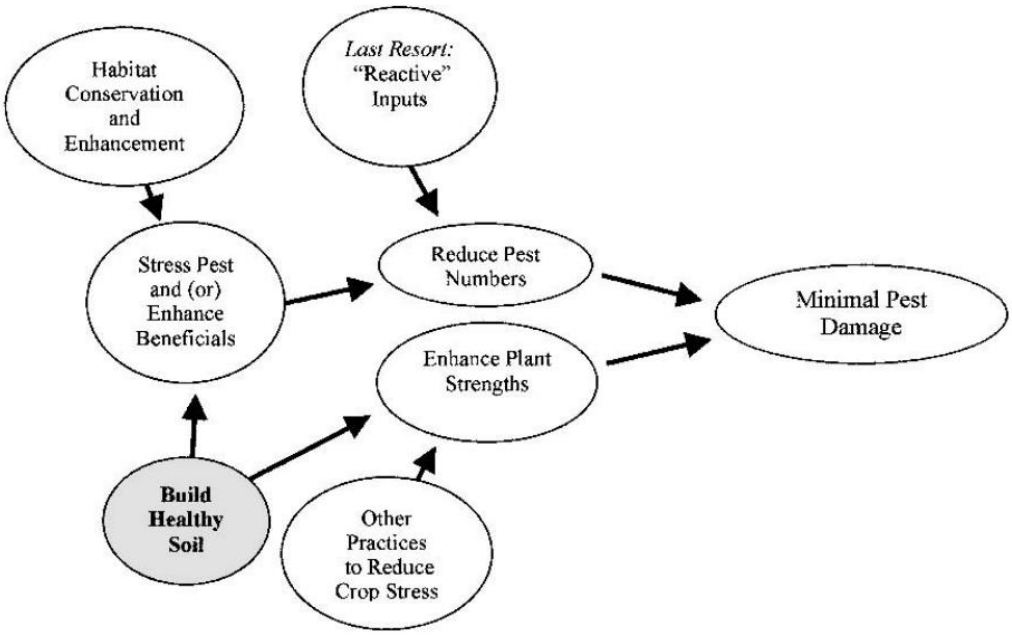

Figure 1. Contribution of soil health to pest management (Magdoff, 2001)

2. Nutrient Management

Having a unique capability to fix atmospheric nitrogen through a symbiotic connection with rhizobia, leguminous cover crops, such as vetch and clover, they can cycle more N to the coming cover crop than non-leguminous cover crops(Clark et al., 2007). By converting atmospheric nitrogen into a form that plants can utilize, this mechanism enriches the soil with nitrogen and reduces the need for synthetic fertilizer. For example, Sorghum Sudan grass (Sorghum bicolor S. Sudanese) increased the macro- and micro-nutrient uptake in Colorado. Copper, manganese, and Zinc of 4%, 19%, and 4% respectively in the cover crop were absorbed by the subsequent potato crop(Delgado et al., 2007). In temperate climates, the cycling of macro and micronutrients from cover crops to the next crop can be substantial (Delgado et al., 2009).

3. Erosion control

Soil erosion causes deforestation, speeds up the loss of soil nutrients and water, contaminates surface waterways, contributes to global environmental changes, and lowers agricultural and environmental productivity. The world's terrestrial ecosystems lose over 75 billion tons of soil annually, predominantly from agricultural lands, with erosion rates ranging from 13 to 40 Mg ha−1 yr−1 (Pimentel et al., 1998). Cover crops are very successful at preventing soil erosion as they provide ground cover that shields the soil from raindrop impact and reduces surface runoff. The efficiency of cover crops in reducing splash and interrill erosion has been shown in numerous studies. During the winter season in temperate climates, cover crops protect the soil against splash erosion and physical degradation, such as aggregate destruction, topsoil compaction, and surface sealing(Kaspar et al., 2001). To prevent soil erosion, cover crops cover the ground with living vegetation and roots (Magdoff & Van Es, 2000). Cover crops and nitrogen fertilizers can increase carbon input and storage in tilled and untilled soils in subtropical humid regions of the Southeastern United States(Sainju et al., 2006).

4. Water Management

Through better water infiltration and decreased surface runoff, cover crops improve soil structure and the soil's ability to store water (Cannon et al., 2023). They increase the amount of organic matter in the soil, which enhances its ability to retain water and is especially advantageous in areas with variable precipitation (Moore & Moore, 2023). Long-term cover management had little effect on the soil microporosity or water content at saturation, however, water content at field capacity did increase slightly. Undisturbed native soils often contain more water than cultivated soils, with restored soils falling somewhere in the middle. However, little research has investigated the impact of cover crops on soil-water use efficiency in temperate rain-fed agricultural systems (Nichols et al., 2022).

5. Weed Control

Cover crops effectively reduce the weed pressure by competing with weeds for key resources such as light, water, and nutrients, resulting in much lower weed growth and establishment. For instance, cover crops like rye and white clover form a dense mat of vegetation that limits light availability to weeds, thereby suppressing their growth(Lemessa & Wakjira, 2014). Furthermore, several cover crops produce allelopathic chemicals that inhibit weed germination and growth. These chemicals can be released through root exudation, leaf leachates, or the decomposition of plant residues. Rye (Secale cereale) and mustard (Brassica spp.) produce allelopathic compounds that suppress weeds (Kelton et al., 2012; Khamare et al., 2022). Cover crop's biomass also acts as a physical barrier, preventing weed seeds from accessing the soil surface and germinating, enhancing weed suppression (Gerhards et al., 2024).

6. Pest and Disease Management

They also act as a habitat and resource for beneficial insects and natural enemies of pests and aid in maintaining and increasing populations of predators and parasitoids that control pest populations. Few studies revealed that cereal rye helps in lowering the pests damage in subsequent cash crops as it supports predatory insects. By covering the soil surface, cover crops can reduce the habitat available for pests, which is particularly effective against soil-borne pests and diseases. Additionally, some cover crops release allelopathic chemicals that can inhibit the growth of pests and pathogens, disrupt the life cycle, and lessen their number and incidence of diseases and pests in following crops (Liburd et al., 2008)(Vukicevich et al., 2016).

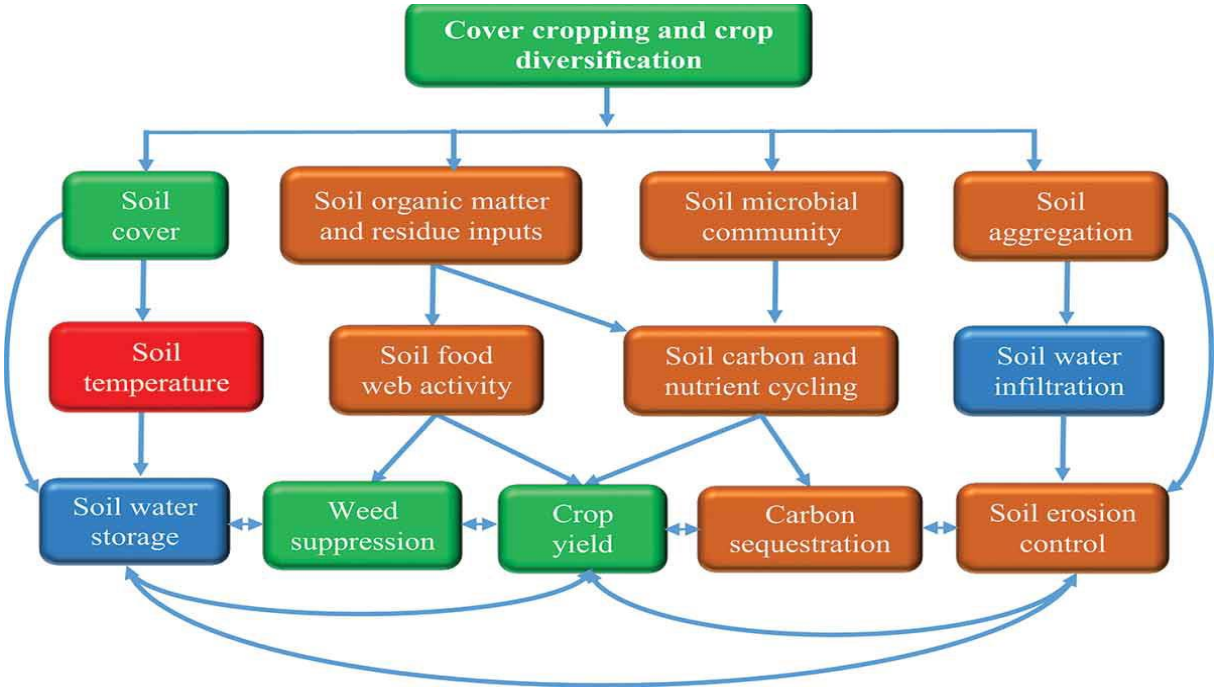

Figure 2. Showing the importance of cover cropping and crop diversification (Ghimire et al., 2018)

Manipulating Cover Crops to Influence Soil Microbial Communities

Plants influence the soil microbial community mainly through root exudates (BADRI & VIVANCO, 2009). The diverse mixture of plants in cover crops can likely aid in maintaining a greater diversity of root-associated bacteria, resulting in better overall benefits because the composition, quantity, and seasonality of exudates change depending on the host plant. For instance, vetch has a substantial influence on soil microbial biomass nitrogen and the total of all fatty acids with more than 14 chains compared to no cover crop (Mbuthia et al., 2015). F. macrophylla shows a relatively higher abundance of copiotrophic members of the phyla Actinobacteria, Bacteroidetes, and proteobacteria, which were positively correlated with an increase in soil organic matter degradation in a rubber orchard(Liu et al., 2019). Similarly, F. arundinacea also increases soil organic matter content by 7% throughout 7 years of application in organic apple orchards(Jones et al., 2017). In addition, cover crop treatments intercropped with crown vetch boosted bacterial populations, resulting in additional pathways for plant degradation and N, P reactions in apple orchards.(Zheng et al., 2018).

Challenges and Limitations of Cover Crops

Though cover crops provide benefits for soil health, weed suppression, and pest management, they come up with challenges that require careful planning and management. These challenges and limitations underscore the complexities of incorporating cover crops into agricultural systems. The use of cover crops is not seen as a radical or transformative technology, nor does it require farmers to significantly alter their choice of annual cash crops, as cover crops are usually grown during fallow periods (Roesch-McNally et al., 2018). Farmers need to adjust their management practices in both fall and spring for the successful integration of cover crops with their cash crops which discourages them from consistently using cover crops for multiple seasons (Dunn et al., 2016). Likewise, the seeding and termination process also incur extra costs. Consequently, the use of cover crops often does not agree with today's farming system, where effort is made to reduce the cost of production for a single crop annually(Roesch-McNally et al., 2018).

In limited rainfall or non-irrigated fields, cover crops compete with main crops for moisture which negatively affects the yield of primary crops. Some cover crops also release chemicals that stop the growth of crops planted later. This allelopathy

needs to be managed to avoid adverse effects on the main crops (Moore & Moore, 2023). Implementing cover crops requires balancing their economic benefits against initial and ongoing costs. Upfront expenses for seeds, planting, and management, along with potential yield reductions due to competition for resources with cash crops, can discourage adoption. However, studies suggest that integrating cover crops is generally profitable in the long term, especially when combined with no-till practices and diverse cropping systems. Long-term benefits often include lower fertilizer and herbicide costs and improved crop yields (Bergtold et al., 2019). Cover crops can present environmental risks, such as harboring pests or diseases that could later impact cash crops. For example, failing to terminate cover crops at the appropriate time can create favorable conditions for pathogens, leading to higher disease pressure on subsequent crops (Garba et al., 2022) (Baraibar et al., 2021).

There are several knowledge gaps in the research on cover crops. One significant gap is the limited region-specific research, which means that the benefits and challenges of cover crops can vary widely depending on local conditions. Additionally, inconsistent results in some systems make it difficult to generalize findings across different agricultural settings. For example, while cover crops can improve soil health and reduce erosion in some regions, these benefits may not be as pronounced in others due to variations in soil type, climate, and management practices.

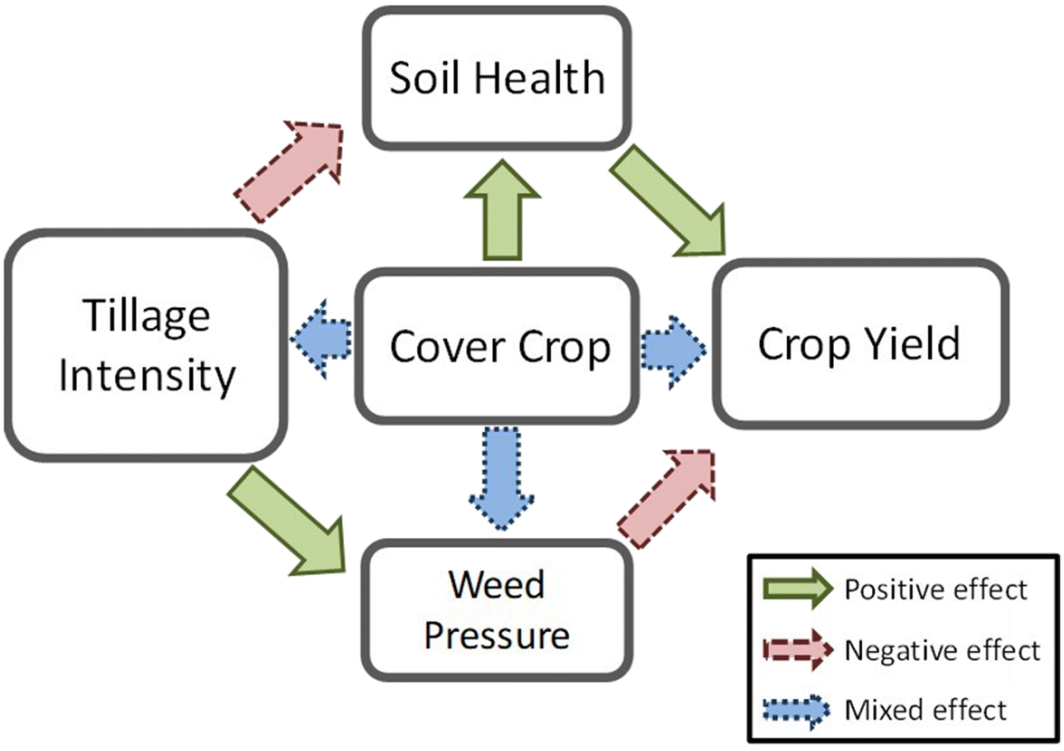

Figure 3. Showing the positive, negative, and mixed effects of using cover crop (Osterholz et al., 2020)

This review provides a comprehensive overview of the existing research on cover crops, highlighting their benefits, challenges, and applications in various agricultural systems. This paper aims to pinpoint areas where current research is lacking or where there are inconsistencies in the findings, better understand the limitations and potential of cover crops to propose directions for future studies. This helps to address the identified gaps, explore new applications, and enhance the effectiveness and adoption of cover crops in sustainable agriculture. By achieving these objectives, the review contributes to the broader understanding of cover crops and their role in addressing global agricultural challenges such as soil degradation, climate change, and food security.

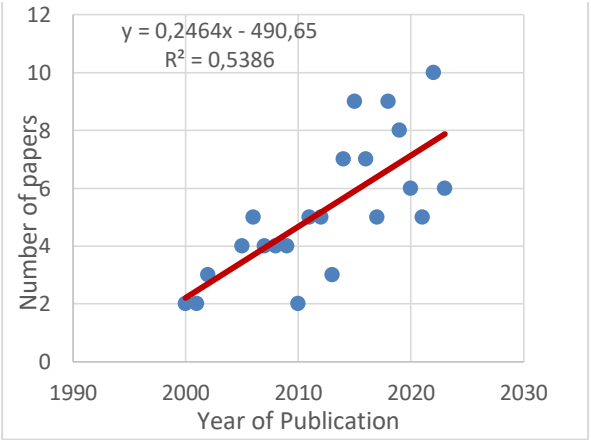

Figure 4. Trend of paper publication about cover crops

The analysis suggests a coefficient of determination (R2) of 0.5386, indicating growing interest in research on cover crops over time. This result suggests a moderate correlation, implying an increasing trend in research interest over time, although other external factors may also affect the publication trend.

CONCLUSION

Cover crops are emerging techniques for improving soil health, crop yield, and the efficiency of weed control. Their ability to suppress weeds through competition for light, water, and nutrients reduces the need for herbicides, supporting sustainable weed management. Several cover crops, like leguminous, grasses, brassicas, and mixtures, help in nutrient management as well as provide nutrients to the soil. Cover crops contribute to carbon sequestration and nitrogen fixation, playing a significant role in mitigating climate change impacts. Past research suggests that long-term adoption of cover crops improves yield, reduces input costs, and makes it a cost-effective practice for farmers. But sometimes, cover crops compete with main crops for moisture, mostly in the limited rainfall region. However, they offer numerous positive impacts, proper management is crucial to reduce negative effects such as excessive moisture competition and delayed cash crop planting. Additionally, if not managed correctly, cover crops can increase disease risk. The increasing trend of studies on cover crops emphasized their growing importance in modern agricultural systems.

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