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Review

Enhancing Agroecosystem Sustainability by Means of Cover Crops in the Era of Climate Change

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Abstract: Climate change has become one of the biggest challenges for farmers, advisors, researchers, and policymakers in recent years. Concerns about food security and the economic future have led these groups to search for methods to adapt to and mitigate climate change. In this context, cover crops have emerged as an important tool to improve soil health, prevent nitrate leaching, and increase crop productivity. The main objective of this review is to explore the multiple benefits of cover crops, including their role in improving soil health, sequestering CO_2, fixing N_2, and enhancing gas exchange, all of which contribute to the sustainability of agricultural systems under climate change conditions. One of the key findings of this research is that cover crop cultivation must be carefully tailored to the specific site, farm, intended purpose, and top priority, taking into account factors such as species selection, crop duration, and termination methods. Certain cover crop species have the potential to mitigate important climate change factors, such as soil erosion and nitrogen leaching, while increasing soil organic matter. However, many studies often focus on only one aspect of cover crops, overlooking the full range of ecosystem services they provide. In addition, future research must also address the economic challenges associated with cover crops.

Keywords: cover crops; climate change; CO_2 sequestration; gas exchange; N_2 fixation

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1. Introduction

Global temperatures have risen, particularly since pre-industrial times, leading to significant climate change [1]. Among the various economic sectors, agriculture is particularly vulnerable to global warming, as it is directly dependent on climatic conditions [1]. Agriculture is considered to be both one of the main drivers of climate change and one of the sectors most affected by it [2]. Globally, agriculture and food production account for around one third of anthropogenic greenhouse gas (GHG) emissions, with 40% attributable to agricultural production and 32% to land use and land-use change [3]. At the same time, rising temperatures, changing precipitation patterns, and the increasing frequency of extreme weather events threaten agricultural productivity, food security, and the livelihoods of farmers worldwide [4]. However, agriculture also holds significant potential for mitigating climate change through sustainable practices that reduce emissions, increase carbon sequestration, and improve resilience.

Climate change mitigation strategies aim to reduce human-induced impacts on the climate system. In agricultural systems, climate change mitigation approaches include reducing nitrogen fertilizer use and associated greenhouse gas emissions, minimizing direct emissions from the soil, and increasing the soil's ability to sequester greenhouse gases [5]. In addition, to reduce the risks associated with both heavy rainfall and drought, management practices that enhance water infiltration, increase soil water storage, and minimize runoff and erosion should be implemented [6]. Another key mitigation strategy involves techniques that reduce CO_2 emissions while preserving soil quality and optimizing resource use [4,7]. Given these approaches, the question is which agricultural practices could simultaneously address all of these climate change mitigation strategies.

The answer probably lies in several practices, with the adoption of cover crops being the cornerstone of various strategies. Cover crops are an old agricultural practice well known for providing many ecosystem services. They are defined as non-harvested crops grown during or between primary cropping seasons to enhance soil health and sustainability [8,9]. Cover crops can be grown and terminated before sowing annual crops such as maize and wheat or grown between trees and vines in perennial cropping systems (in which case often characterized as companion crops). Cover crops do not usually provide direct income to farmers and are grown for their ecosystem services in order to enhance the overall sustainability of agricultural production [10]. Moreover, they can be adapted to diverse climatic conditions and agroecosystems, including semi-arid regions before an irrigated summer cash crop, cold-temperate areas before a spring cereal crop, tropical and subtropical zones before a rain-fed summer crop, and even rice paddies during the fallow season [7]. Cover crops are generally composed of legumes (Fabaceae), grasses (Poaceae), and brassicas (Brassicaceae) plant families [11]. The practice of cover cropping has been used since ancient times in the Mediterranean, where leguminous plants were ploughed into fallow fields after an early harvest in order to reinvigorate the soil [8,12]. Similarly, writings from ancient China document the use of non-harvested plants as green manure to improve soil fertility [13]. During the following two thousand years, cover crops became a common practice in European agriculture and were probably brought to the United States by early colonists in the 1600s [13]. In the early years, farmers relied on leguminous crops such as peas (*Pisum sativum*), clover (*Trifolium* sp.), and lentils (*Lens culinaris*) to naturally restore soil fertility and support grain production [14]. By 1929, researchers began exploring the benefits of both legume and non-legume cover crops for soil enhancement [13].

This review aims to explore and present the role of cover crops as an agroecological practice in mitigating the impacts of agriculture on climate change while simultaneously enhancing agricultural resilience to the adverse effects of climate change. As Kaye et al. [5] noted, while mitigation cannot eliminate the anthropogenic impact on climate change, implementation of adaptive practices can enhance the resilience of agricultural systems or even redesign them to adapt to emerging climate conditions. This review examines some of the environmental benefits of cover cropping, focusing on its ability to reduce greenhouse gas emissions, improve soil health, increase biodiversity, and enhance water management. This manuscript synthesizes existing literature by selecting studies that highlight the benefits and challenges associated with cover crops in the context of climate change. The manuscript is structured as follows: after this introduction, we present an overview of the environmental benefits of cover crops, followed by the best cover crop species for climate change mitigation and suggestions for future research.

2. Cover Crop Benefits and Environmental Impacts

The benefits of cover crops are increasingly recognized over time, especially in their ability to enhance soil health and promote the sustainability of agricultural systems. Legume cover crops convert atmospheric nitrogen into a plant-available form through a symbiotic relationship with rhizobia in their root nodules. The fixed N can benefit non-legumes in mixed cropping systems or serve as a nutrient source for subsequent crops in rotational systems [15]. As a result, the use of synthetic nitrogen in the subsequent crops, such as maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), or soybeans (*Glycine max* L.) is reduced [15]. Non-leguminous species with deep taproots (e.g., oats (*Avena sativa)* and white mustard (*Sinapis alba)*) scavenge nutrients from deeper soil layers, recycle existing nitrogen, and help to prevent excessive leaching into groundwater systems [9,16]. As an agroecological and environmentally friendly practice, cover crops improve soil fertility while providing additional benefits. In particular, they can also contribute to higher yields of subsequent crops, which are usually cereals, while reducing land use requirements, such as the need for additional nitrogen inputs and machinery operations [3,17]. All cover crops produce considerable biomass due to their photosynthesis, which helps to increase the accumulation of soil organic matter [15]. Furthermore, in addition to their many ecosystem services, cover crop mixtures play a crucial role in improving weed suppression and reducing the need for herbicides [10]. Another benefit of using cover crops is their ability to suppress weeds by competing for resources and space [18]. They can also limit the production of weed seeds from summer and winter annual species, reducing the growth of weed populations and ultimately weed pressure on future crops [19]. Research has shown that the success of cover crop mixtures in suppressing weeds depends on a complex interaction between resource availability and the characteristics of both cover crops and weed species [18]. However, a study by Smith et al. [20] suggests that a weed-suppressive cover crop grown as a monoculture is more effective in suppressing weeds compared to a mixture.

It is important to note that the feasibility and effectiveness of cover crops depend heavily on site-specific factors such as climate and soil type [5]. In line with this, Teixeira et al. [21] identified sowing dates as the primary contributor to variability in cover crop effectiveness, followed by weather conditions, factor interactions, and soil water-holding capacity. Another study also found that cover crop biomass was influenced by the local soil and climate conditions [22]. These findings underscore the need to consider local environmental conditions when evaluating or implementing cover crop strategies.

2.1. Impact of Cover Crops on Soil Erosion

The improvement in soil structure through their root morphology is another important advantage of cover crops [14]. Poaceae species such as rye (*Secale cereale* L.) have a dense, fibrous root system that increases the porosity of the soil, thus promoting water infiltration and storage. Brassicaceae species, such as radish, develop deep taproots that can penetrate compacted soil layers, improving water drainage and increasing soil aeration [23]. These physical improvements help reduce surface runoff and erosion by stabilizing soil aggregates and facilitating water movement within the soil profile [14]. Studies have shown that cover crops can reduce erosion from rainfall by up to 95% [6]. In tropical regions with intense rainfall, the protective canopy and root systems of cover crops are particularly effective in mitigating water erosion by intercepting raindrops and reducing the detachment of soil particles [17]. In addition, the increase in wind activity due to climate change has increased the risk of wind erosion in certain areas. Cover crops with high residue content, such as rye, can minimize this risk by maintaining continuous ground cover and reducing wind speed at the soil surface [17]. Mixed non-legume cover crops, such as radish and rye, can benefit soil health by preventing both soil erosion and soil compaction, due to the bio-drilling potential of radish (*Raphanus sativus* L.) and the production of abundant aboveground biomass by rye [15]. Table 1 provides a summary of the different cover crop types, their associated benefits, and their impacts on soil health and the environment.

Table 1. Benefits and environmental impacts of different cover crop types.

Cover Crop Type	Benefit	Impact on Soil Health	Environmental Impact
Legume	• Nitrogen fixation	• Enhanced nutrient cycling	• Reduced N_2O emissions • Reduced fertilizer use • Enhanced carbon sequestration
Grass–legume	• Nitrogen fixation • Erosion control • Deep-rooted nutrient scavenging	• Improved soil structure • Increased soil organic matter content • Improved water infiltration • Increased productivity	• Enhanced carbon sequestration • Reduced nitrate leaching • Increased biodiversity

2.2. Impact of Cover Crops on Carbon Sequestration

In addition, cover crops can effectively sequester CO_2 from the atmosphere and store it in the soil in the form of organic carbon by reducing erosion rates [5,17,24]. Sustainable practices such as organic farming, cover cropping, and reduced tillage can improve the ability of soil to sequester CO_2, while detrimental practices such as overgrazing, intensive tillage, or land conversion can reduce its ability to store carbon [25]. By increasing soil organic carbon (SOC) storage and improving overall soil health, cover cropping can be considered a viable strategy to mitigate climate change [3].

A global meta-analysis by Poeplau and Don [26] has shown that cover crops have contributed to an increase in soil carbon of about 0.32 Mg ha^{-1} at a depth of 0–22 cm over several decades, highlighting their role in carbon sequestration. Additionally, a simulation study revealed that cover crops reduced carbon mass by 3% compared to a 6% decrease in systems without cover crops [6]. However, the impact of cover cropping on soil carbon storage can vary across different sites, with more significant benefits observed when paired with practices such as reduced tillage, diverse crop rotations, and higher nitrogen inputs [5].

Shifting from traditional monoculture and fallow systems to more diversified cropping systems can further enhance carbon sequestration by maximizing biomass production and soil organic matter accumulation. A substantial portion of the depleted SOC pool can be restored through the conversion of marginal lands into restorative land uses, the adoption of conservation tillage, and the integration of cover crops with crop residue mulching [27]. However, cover crops may need to be used for decades in some systems to cause significant SOC increases [28]. While cover crops alone may not be sufficient to turn croplands from carbon sources into carbon sinks, they effectively reduce bare fallow periods and SOC losses, making them a valuable tool for agricultural climate change mitigation [29,30].

2.3. Impact of Cover Crops on Gas Exchange

A considerable aspect of climate change involves not only the changes in soil parameters but also the emissions of greenhouse gases. Over the past few decades, the atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gases has risen dramatically [27]. Given that soil carbon sequestration is difficult to quantify and verify in the long term, it may be considered challenging to quantify and verify over long periods, making it a less immediate solution for climate change mitigation [25]. Therefore, in the short term, mitigation strategies may be more effectively directed toward reducing atmospheric CO_2 concentrations. Restoring lost carbon in cropland soils can serve as a valuable strategy for capturing and storing atmospheric carbon [28]. Cover crop cultivation, an agroecological management practice, has the potential to sequester atmospheric CO_2, reduce the climatic footprint of agroecosystems, and contribute to climate change mitigation [15,30]. In addition to enhancing soil health and carbon sequestration, cover crops contribute to climate change mitigation through their higher albedo effect, reflecting more shortwave radiation (0.08–0.22 Wm^{-2}) back into space compared to bare soil, a quantity that is broadly equivalent to the removal of 0.8–3.9 Mg CO_2e ha^{-1} [31]. For long-term carbon sequestration, the CO_2 removed from the atmosphere through photosynthesis must be incorporated into stable organic matter pools with long turnover rates, forming long-lived SOC [32]. Higher SOC levels enhance soil structure, water retention, and nutrient availability, creating more resilient cropping systems while reducing greenhouse gas emissions.

While carbon sequestration through cover crops plays a vital role in mitigating climate change, it is equally important to consider the impact of agricultural practices on other greenhouse gases, such as nitrous oxide (N_2O), which also contribute to global warming. Agricultural soils are a major source of N_2O emissions, a potent greenhouse gas with a long atmospheric lifespan [5]. N_2O emissions saw an increase of 0.8% in 2018 as compared to a 1% annual increase over the past decade [4]. This occurs because nitrogen (N) is a vital nutrient for agricultural productivity. It enters the soil through fertilizers and manure, is released from decomposing organic matter, and exhibits high reactivity and mobility within terrestrial ecosystems [33]. These emissions primarily result from the denitrification of nitrate, a process that occurs more rapidly in water-saturated soils. By reducing both soil moisture and nitrate levels, cover crops can help lower N_2O fluxes from the soil to the atmosphere [5]. Additionally, they contribute to reducing indirect N_2O emissions by minimizing NO_3^- leaching while enhancing carbon sequestration through increased photosynthetic activity [15]. This highlights their role as a key strategy for mitigating agricultural greenhouse gas emissions and improving overall soil health. However, Schon et al. [3] pointed out that cover cropping can, under certain weather conditions—such as variations in air temperature and soil moisture—lead to increased N_2O emissions. The increase in these emissions also depends on the carbon-to-nitrogen (C/N) ratio of the cover crop and the treatment of cover crop residues. Specifically, incorporating cover crop residues into the soil tends to increase N_2O emissions compared to leaving them on the surface to decay naturally [3].

2.4. Impact of Cover Crops on Nitrate Leaching and Nitrogen Fixation

In addition to their role in mitigating greenhouse gas emissions, certain cover crops, particularly legumes, play a crucial role in biological nitrogen fixation, a natural process that converts atmospheric nitrogen (N_2) into plant-available forms, reducing the need for synthetic fertilizers. Approximately 50% of applied N fertilizer is lost from agricultural lands [34]. Furthermore, leaving fields fallow can lead to excessive nutrient and nitrogen leaching, further contributing to environmental degradation [34]. Reducing nitrogen (N) inputs and losses from agriculture is essential for sustainable development, as excessive nitrogen can harm the aquatic environment and biodiversity and contribute to climate change [35]. Long before nitrogen became acknowledged as an environmental concern, researchers had already documented the ability of cereal grain cover crops to mitigate nitrate leaching from the root zone [34]. Most of the leaching occurs during the late fall and winter [34], a period ideally suited for sowing cover crops. Research has shown that grass–legume cover crops offer an advantage by not only fixing nitrogen but also retaining it within the agroecosystem [36,37]. These mixed cover crops enhance productivity, increase total nitrogen availability, and improve nitrogen fixation compared to legume monocultures, making them a promising strategy for sustainable nutrient management [38].

3. Best Cover Crop Species for Climate Change Mitigation

The selection of the right cover crop species is essential for maximizing the potential of cover crops in climate change mitigation. Different species provide unique benefits depending on their growth habits, nutrient cycling capabilities, and environmental conditions. By choosing the best cover crop species tailored to specific agroecosystems, farmers can enhance soil health, improve carbon sequestration, reduce greenhouse gas emissions, and promote overall sustainability. This section explores the most effective cover crop species for climate change mitigation, focusing on their roles in carbon sequestration, nitrogen fixation, and soil health improvement.

One important aspect of climate change mitigation through cover crops is carbon sequestration, which is influenced by both cover crop species and rotational practices [28]. Studies have shown that different cover crop types can result in varying soil organic carbon (SOC) increases. For instance, grass cover crops such as cereal rye and annual ryegrass (*Lolium multiflorum* Lam.) have been associated with greater SOC accumulation compared to leguminous cover crops like cowpea (*Vigna unguiculata* L.) and hairy vetch (*Vicia villosa* Roth.) [28]. This finding is further supported by a meta-analysis review conducted by Schon et al. [3] which confirmed that grass cover crops lead to 2.3 times higher SOC sequestration than legume cover crops. In another study, researchers found that barley (*Hordeum vulgare* L.), rye, and triticale (×*Triticosecale Wittmack*) achieved high ground cover (83–99%) and biomass production (1226–1928 g/m^2), highlighting their high productivity and significant soil coverage. With a high carbon-to-nitrogen (C:N) ratio (28:40), their residues decompose more slowly, contributing to soil protection and organic matter buildup [39]. Barley and vetch in mixed cover crops in olive groves enhanced SOC and decreased the C:N ratio [40]. The mitigation efficacy of barley as a cover crop is mainly attributed to its role in carbon sequestration [7], further highlighting the importance of grass species for increasing SOC.

On the other hand, Mazzoncini et al. [41] observed that leguminous cover crop systems resulted in significantly higher SOC concentrations compared to non-legume cover crop systems. Interestingly, mixtures of grass and legume cover crops often result in the greatest SOC accumulation, suggesting that diversity in cover crop species may be an effective strategy for optimizing carbon sequestration in agricultural soils [28]. Bodner et al. [42] examines the rooting patterns of different cover crop species. Rye and phacelia (*Phacelia tanacetifolia* Benth.) had the highest density in surface roots, making them better species for soil erosion problems compared to vetch and mustard.

Beyond carbon sequestration, cover crops also offer a range of other environmental benefits that contribute to climate change mitigation. One key advantage is their ability to reduce N_2O emissions, a major contributor to the global warming potential of agricultural cropping systems [33]. However, the impact varies depending on the cover crop species and management practices. Research has shown that legume cover crops, such as vetch, tend to increase N_2O emissions—especially under low nitrogen input or when residues are incorporated into the soil—while non-legumes, like barley, generally contribute less to emissions unless incorporated [5,7,43]. Higher precipitation levels also amplify N_2O release due to elevated soil moisture [44]. However, at the scale of an entire crop rotation, the overall effect of cover crops on N_2O emissions appears to be minimal, as confirmed by Peyrard et al. [44]. Given these findings, non-legume cover crops or mixed legume–non-legume systems appear more suitable for minimizing emissions while preserving soil benefits.

In addition to carbon sequestration and reducing greenhouse gas emissions, cover crops, particularly legumes, play a crucial role in nitrogen fixation, further enhancing the sustainability of agricultural systems. The amount of nitrogen fixed varies depending on the species of legume used and, in the case of mixtures, the specific companion crop species involved [3]. In a study evaluating winter annual legumes in cold climates, hairy vetch (*Vicia villosa* Roth) outperformed medium red clover (*Trifolium pratense* L.) in nitrogen fixation, contributing up to 211 kg N ha^{-1} from its aboveground biomass, highlighting its potential as a valuable nitrogen source in short-season cropping systems [38]. Additionally, red clover, when used as a monoculture cover crop, has been found to fix 29 kg N ha^{-1}, but in a mixture with ryegrass, this amount has been shown to increase to 52 kg N ha^{-1}, demonstrating the added nitrogen-fixing potential of mixed systems [3]. Moreover, five legume species—*Pisum sativum* L., *Vicia sativa* L., *Lathyrus sativus* L., *Vicia villosa* Roth., and *Vicia faba* L.—were found to fix more than 100 kg N ha^{-1}, compared to chickpea (*Cicer arietinum* L.), which accumulated only 16 kg N ha^{-1} [45]. At the same time, the nitrogen absorbed from the soil by these legumes can reach levels comparable to those observed in non-legume plants. In particular, soybean removed an average of 70 kg N ha^{-1} from the soil over a 3-month period, more than oat and phacelia [45]. This suggests that soybeans are an effective option for managing excess nitrogen, helping to prevent nutrient imbalances and reduce the risk of nitrate leaching. Vetch, on the other hand, exhibited low nitrogen uptake from the soil (2.4 and 0.7 g N/m^2), making it a more suitable choice for an adaptive climate change strategy [39]. Also, mustard as cover crop has demonstrated strong nitrogen uptake in warmer years, indicating its potential under increasing temperatures. However, its vulnerability to winter frost may reduce its reliability for consistent nitrogen recovery across variable climatic conditions [39]. This suggests that mustard can be beneficial for managing excessive nitrogen and preventing nitrogen leaching in climate change conditions, under increasing temperatures. However, it may not be the best choice if the subsequent crops require nitrogen, as mustard could deplete nitrogen levels in the soil. These values, however, may vary depending on factors such as plant density, percentage of ground cover, and biomass production.

Understanding how different species interact with nitrogen is crucial for addressing these challenges and empowering farmers to make informed decisions for sustainable agricultural practices. The choice of an optimal cover crop depends on its intended purpose, soil conditions, and regional climate [11]. Legume cover crops contribute to climate change mitigation primarily by reducing the need for synthetic nitrogen fertilizers in subsequent cash crops, thereby lowering indirect N_2O emissions from nitrate leaching while also enhancing carbon sequestration [7]. Additionally, since land-use change remains the largest source of carbon emissions in the agri-food system, the yield improvements associated with cover crop adoption can help offset these emissions, making them a valuable strategy for sustainable agriculture [17] (Table 2). In all cases, spontaneous vegetation can also play the role of cover cropping and has been recently suggested as an innovative way to enhance ecosystem services toward resilience and climate change mitigation [46].

Table 2. Best cover crop species for climate change mitigation.

Cover Crop Species	Purpose
Rye	Increasing SOC
Annual ryegrass	Increasing SOC
Barley	Increasing SOC, lowering emissions
Barley and vetch mixture	Enhancing SOC and decreasing the C:N ratio
Rye and phacelia mixture	Preventing soil erosion
Vetch	Increasing N_2O emissions, high N_2 fixation
Soybean	N_2 fixation, preventing N leaching
Mustard	Preventing soil erosion and N leaching

4. Future Research

Future research should focus on long-term studies to better understand how cover crops influence nitrogen and other nutrient cycling, soil organic matter dynamics, carbon sequestration, greenhouse gas emissions, and crop yields over multiple decades. While previous studies have demonstrated the beneficial effects of cover cropping for climate change mitigation, there remain significant knowledge gaps. For example, studies have assessed different cover crop species, including legume–cereal mixtures, but have failed to make comparisons with bare soil and have omitted several greenhouse gas components. Addressing these gaps through comprehensive, long-term field trials will provide more accurate assessments of the full climate benefits of cover cropping and guide the development of more effective, science-based agricultural policies. Additionally, future research should explore how cover cropping can be effectively combined with other sustainable agricultural practices to enhance climate change mitigation. Long-term field trials that assess the cumulative benefits of multiple mitigation strategies will be essential for guiding farmers and policymakers toward the most effective and scalable solutions for sustainable agriculture in a changing climate. Also, studies about the economic impact of incorporating cover crops into crop production are required.

5. Conclusions

According to the literature, cover crops have climate-change-mitigation properties. The selection of appropriate cover crop species is crucial for maximizing their climate change mitigation potential. Among the most effective species, grasses such as cereal rye and barley have shown superior carbon sequestration capabilities, making them ideal choices for increasing SOC levels. Additionally, legume cover crops, including vetch and red clover, contribute significantly to nitrogen fixation, reducing the need for synthetic nitrogen fertilizers and minimizing nitrogen-related emissions. While legumes can sometimes lead to increased N_2O emissions, incorporating them into mixed cover crop systems alongside grasses can help optimize soil health benefits while mitigating potential drawbacks. However, cover cropping alone is not a silver bullet for climate change mitigation. To achieve meaningful and long-term sustainability, it must be integrated with other agricultural practices. These include conservation tillage, diversified crop rotations, agroforestry, efficient nutrient management, and organic farming. Combining these strategies can enhance soil health, boost carbon sequestration, and minimize greenhouse gas emissions more effectively than any single practice alone.

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Abbreviations

The following abbreviations are used in this manuscript:

SOC	Soil organic carbon
CO_2	Carbon dioxide
N_2O	Nitrous oxide
N_2	Nitrogen

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