REVIEW ARTICLE

From Degradation to Regeneration: Agronomic Practices Supporting Soil Health and Biodiversity Recovery

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Summary
This paper examines regenerative and conservation agriculture as approaches to mitigate soil degradation, biodiversity loss, and climate change. Both systems rely on minimal soil disturbance, permanent soil cover, and crop diversification, improving soil organic carbon, structure, and biological activity. These practices enhance biodiversity and ecosystem services while supporting climate mitigation through carbon sequestration and increased resilience. Key limitations include the lack of standardized indicators and insufficient long-term field studies. Future research should focus on integrative, region-specific approaches to better quantify impacts and support wider implementation.

Keywords: regenerative agriculture, conservation agriculture, carbon sequestration, climate change, ecosystem services

Introduction

Soil degradation and biodiversity loss are among the most critical challenges confronting modern agricultural systems, threatening ecosystem stability, climate resilience, and long-term food security (Jug et al., 2022). Intensive agricultural practices, such as frequent tillage, simplified crop rotations, excessive use of mineral fertilizers, and insufficient organic matter inputs, have led to declines in soil organic carbon (SOC), deterioration of soil structure, increased erosion, and disruption of soil biological communities (Montgomery, 2007; Lal, 2015). These processes are particularly evident in European agroecosystems where long-term conventional management has increased the vulnerability of structurally sensitive soils and contributed to widespread soil degradation (Orgiazzi et al., 2017). At the same time, agricultural intensification has accelerated biodiversity loss, weakening key ecosystem services such as nutrient cycling, pollination, and biological pest control (Bardgett and van der Putten, 2014; IPBES, 2019). In response, regenerative agriculture (RA) and conservation agriculture (CA) have emerged as complementary, systems-based approaches aimed at restoring soil health, enhancing biodiversity, and improving ecosystem services. CA is founded on minimal soil disturbance, permanent soil cover, and crop diversification, while RA builds upon these principles by integrating additional practices such as organic amendments and, in some cases, livestock inclusion (FAO, 2021). Together, these practices improve soil structure, increase SOC sequestration, enhance water retention, and stimulate biological activity (Paustian et al., 2016; Lal, 2020). Recent studies confirm that RA and CA practices can significantly improve soil health and promote biodiversity recovery (Colombi et al., 2025; Hawes et al., 2025), while also contributing to climate change mitigation and resilience (Bossio et al., 2020; Berthon et al., 2025). However, their effectiveness remains highly context-dependent, varying with soil type, climate, and management history (Lemke et al., 2024; Kumar et al., 2025).
Therefore, there is a need for integrative and region-specific research linking agronomic practices with measurable changes in soil health and biodiversity. The objective of this review

is to evaluate the agronomic principles of RA, in relation to CA, and their role in reversing soil degradation and biodiversity loss.

Agronomic Principles of Regenerative Agriculture in relation to Conservation Agriculture

RA is based on interrelated agronomic principles aimed at restoring soil functionality, enhancing ecosystem resilience, and ensuring long-term agricultural sustainability. CA represents a key foundation of this approach, as both systems share core principles: minimal soil disturbance, permanent soil cover, and crop diversification (Hobbs et al., 2008; FAO, 2021). While CA focuses on these three pillars, RA expands them by incorporating livestock, organic amendments, and broader ecosystem restoration (Palm et al., 2014). Minimal soil disturbance, achieved through conservation tillage, is fundamental to both systems. Conventional plowing disrupts soil structure and accelerates organic matter mineralization (Lal, 2015), whereas conservation tillage improves aggregate stability and promotes carbon retention (Paustian et al., 2016). However, its benefits are maximized when combined with soil cover and crop diversification (Pittelkow et al., 2015; Nunes et al., 2018). Permanent soil cover, maintained through residues or cover crops, protects soil from erosion, regulates temperature, and reduces water loss, while increasing soil organic carbon inputs (Lal, 2020). Cover crops also enhance microbial activity, support biodiversity, and suppress weeds (Kumar et al., 2025). Crop diversification further strengthens system resilience by improving nutrient cycling, reducing pest pressure, and promoting biodiversity (Bardgett and van der Putten, 2014; Palm et al., 2014). RA extends these benefits through livestock integration, which enhances nutrient cycling and carbon sequestration (Teague et al., 2016), and through organic amendments that improve soil fertility and structure. Overall, CA provides the structural basis for RA, while regenerative practices broaden its ecological and functional scope. Their relationship is complementary, combining agronomic stability with enhanced ecosystem restoration and climate resilience.

Regenerative and Conservation Agriculture and Soil Health

Soil health is a multidimensional concept encompassing physical, chemical, and biological properties, all of which are strongly influenced by regenerative and conservation agricultural practices. One of the most significant effects of these practices is the increase in SOC, which represents a key indicator of soil quality and functionality. Higher SOC levels improve nutrient cycling efficiency by supporting microbial-mediated processes and increasing nutrient availability, thereby reducing the dependence on external inputs. In addition to chemical improvements, regenerative and conservation practices positively affect soil physical properties. Enhanced soil structure, increased porosity, and improved aggregate stability contribute to better water infiltration and retention. These changes reduce the susceptibility of soil to erosion and improve its capacity to store plant-available water, which is especially important under conditions of increasing climate variability and drought stress (Lal, 2020). Improved physical conditions also facilitate root growth and enhance overall plant performance. Soil biological activity represents another critical dimension of soil health influenced by regenerative and CA. Soil organisms, including microorganisms and macrofauna, play a central role in decomposition processes, nutrient mineralization, and the formation of stable soil aggregates. Regenerative systems promote higher microbial biomass, increased enzymatic activity, and greater diversity of soil fauna, all of which contribute to improved soil functionality and resilience (Bardgett and van der Putten, 2014; Hawes et al., 2025). Collectively, these physical, chemical, and biological improvements demonstrate the integrative impact of regenerative and conservation practices on soil health and their potential to support sustainable agricultural systems.

Regenerative and Conservation Agriculture and Biodiversity Recovery

Biodiversity is a key indicator of agroecosystem sustainability, reflecting the capacity of agricultural systems to maintain ecological balance and provide essential ecosystem services. RA enhances biodiversity through increased habitat heterogeneity and reduced disturbance, and is closely linked to CA, which is based on minimal soil disturbance, permanent soil cover, and crop diversification (Hobbs et al., 2008; FAO, 2021). Together, these approaches create favorable conditions for diverse biological communities. In the soil environment, conservation tillage and increased organic inputs, such as crop residues and manure, support a wide range of organisms, including bacteria, fungi, and soil fauna. These organisms play a central role in nutrient cycling, organic matter decomposition, and soil aggregation, thereby improving soil functionality and resilience (Palm et al., 2014). Increased soil biodiversity also enhances ecosystem stability through functional redundancy. Aboveground biodiversity is similarly influenced by these practices. Crop diversification, cover crops, and reduced chemical inputs increase habitat availability for pollinators and beneficial organisms. Long-term studies confirm higher species richness and functional diversity under regenerative systems (Hawes et al., 2025), while diverse plant communities strengthen above–belowground interactions. Enhanced biodiversity directly contributes to improved ecosystem services, including nutrient cycling, pollination, and natural pest control. These processes reduce dependency on external inputs and increase system resilience to environmental stress (IPBES, 2019; Colombi et al., 2025). Consequently, RA and CA are increasingly recognized as nature-based solutions for climate change mitigation and adaptation.

Regenerative and Conservation Agriculture and Climate Change Mitigation

RA is increasingly recognized as a nature-based solution for climate change mitigation and adaptation due to its capacity to enhance soil carbon storage, improve system resilience, and reduce greenhouse gas emissions. It is closely linked with CA, which is based on minimal soil disturbance, permanent soil cover, and crop diversification - principles that support carbon sequestration and climate resilience (Hobbs et al., 2008). Soils represent one of the largest terrestrial carbon sinks, and practices such as reduced tillage, cover cropping, and the application of organic amendments can significantly increase SOC. The accumulation of SOC improves soil fertility and structure while contributing to the reduction of atmospheric CO_2 concentrations (Bossio et al., 2020). In addition, improved soil structure, increased porosity, and higher water-holding capacity enhance the resilience of agroecosystems to climate variability and extreme weather events, such as drought and heavy rainfall (Kumar et al., 2025). Core elements of CA, particularly reduced soil disturbance and continuous soil cover, play a crucial role in stabilizing soil carbon and minimizing losses (Pittelkow et al., 2015). Regenerative systems further contribute to climate mitigation by reducing dependence on synthetic inputs and improving nutrient-use efficiency. Enhanced biological activity supports more efficient nitrogen cycling and can reduce nitrous oxide emissions, although outcomes remain highly site-specific (Berthon et al., 2025). Overall, CA provides the agronomic foundation for regenerative systems, while RA expands its role by integrating additional practices aimed at maximizing climate mitigation and adaptation benefits.

Limitations and Challenges of Regenerative and Conservation Agriculture

Despite their considerable potential, RA and CA face several limitations and challenges that may affect their adoption and long-term effectiveness. One of the primary constraints is strong context dependency, as the outcomes of these practices vary significantly depending on soil type, climatic conditions, and previous management history. This variability makes it difficult to generalize results and requires site-specific adaptation to achieve optimal benefits (Lemke et al., 2024). Similar challenges have been reported in CA, where the effectiveness of practices

such as no-till and crop diversification depends on local agroecological conditions (Hobbs et al., 2008). Another important limitation is the transition period from conventional to regenerative or conservation systems. During this phase, farmers may experience temporary yield reductions and increased economic uncertainty, particularly in the absence of technical support or financial incentives. The time required for improvements in soil properties and biological communities may delay the realization of full system benefits. A further challenge is the lack of standardization in defining and assessing RA. While CA is clearly defined through its three core principles (FAO, 2021), RA lacks a universally accepted framework and consistent indicators for evaluating its impacts. This complicates comparisons across studies and hinders the development of policies and certification systems. Finally, significant knowledge gaps remain, particularly regarding long-term and region-specific effects of both regenerative and conservation systems. Limited availability of long-term field experiments and integrative studies restricts the understanding of system performance under diverse conditions. Addressing these gaps is essential for developing robust, science-based recommendations and supporting the wider adoption of sustainable agricultural practices.

Conclusions

RA, closely linked to CA, represents an effective approach for addressing soil degradation, biodiversity loss, and climate change. By applying key principles such as reduced soil disturbance, permanent soil cover, and crop diversification, these systems improve soil health, enhance biodiversity, and strengthen ecosystem services. However, their effectiveness is highly context-dependent, and further long-term, region-specific research and standardized assessment methods are needed to support wider adoption and implementation.

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