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Regenerative Agriculture for Climate-Resilient Farming : A Synthesis of Environmental, Agronomic, and Economic Outcomes

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ABSTRACT

Conventional input-intensive farming has substantially boosted global food production, but at the cost of soil degradation, biodiversity loss, water pollution, and rising greenhouse gas (GHG) emissions. Around 30–33% of the world's soils are now moderately to highly degraded, while agrifood systems contributed about 16.5 Gt CO_2-eq in 2023, roughly one-third of total anthropogenic emissions. Regenerative agriculture (RA) has emerged as a promising paradigm that aims to restore soil health, enhance biodiversity, sequester carbon, and improve farm resilience and profitability through a suite of ecologically grounded practices. This review synthesizes recent evidence (2020–2025) on the principles, practices, and outcomes of RA, drawing on meta-analyses and case studies from different agro-ecological regions. Core RA principles include minimizing soil disturbance, maintaining permanent soil cover, diversifying plant species, keeping living roots in the soil, integrating livestock, and reducing or eliminating synthetic inputs. Recent global and regional assessments show that conservation tillage, cover cropping, organic amendments, diversified rotations, and integrated crop–livestock and agroforestry systems can increase soil organic carbon (SOC) by 4–20%, improve yields by 2–30% in the medium term, and reduce nitrous oxide and methane emissions compared with conventional systems, though responses remain context-specific. Economic evaluations indicate that RA can enhance profitability over 5–10 years by lowering input costs, stabilizing yields, and opening access to carbon and sustainability markets, despite higher transition costs and knowledge requirements. Large-scale initiatives such as Andhra Pradesh Community Managed Natural Farming (APCNF) in India demonstrate the potential of state-supported, community-managed regenerative transitions spanning millions of farmers and hectares. Key challenges include definitional ambiguity, variable evidence on yield impacts in the short term, limited data from the Global South, and policy and market barriers. The paper concludes that regenerative agriculture, if supported by robust science, enabling policies, and inclusive value chains, can be a key pathway to future farming systems that are productive, climate-resilient, and socially just.

Keywords : Regenerative agriculture, soil health, carbon sequestration conservation tillage, cover crops, natural farming, climate change

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Introduction

Global food systems face a triple crisis of environmental degradation, climate change, and social inequity. Approximately 30–33% of the world's soils are moderately to highly degraded due to erosion, loss of organic matter, salinization, compaction, and pollution. In India alone, about 96–98 million ha, roughly 29–30% of the geographical area, are undergoing land degradation, with significant implications for crop productivity, water security, and rural livelihoods (Niti Aayog and ICFRE, 2024). At the same time, agrifood systems are major contributors to climate change. Recent FAO estimates indicate global agrifood system emissions of about 16.5 Gt CO_2-eq in 2023, with crop and livestock activities within the farm gate contributing around 8.1 Gt CO_2-eq, nearly half of the total (FAO, 2025). Projections suggest that if current trajectories continue, global warming could exceed 3°C by 2100, with severe implications for agricultural production and food security (Goar, 2024).

These converging pressures have stimulated interest in farming systems that regenerate, rather than deplete, ecological foundations. Regenerative agriculture (RA) is increasingly promoted by scientists, civil society, private companies, and governments as a holistic framework to restore soils, enhance biodiversity, and mitigate climate change while sustaining farmer incomes. The global regenerative agriculture market, encompassing practices, advisory services, and carbon projects, is projected to grow from about USD 5–10 billion in 2025 to over USD 20–30 billion by 2034–35, with compound annual growth rates above 15% (Future Market Insights, 2025). This review aims to (i) clarify the concept and principles of RA, (ii) synthesize recent empirical evidence on its environmental and economic outcomes, (iii) discuss socio-political and policy dimensions, with emphasis on emerging economy contexts, and (iv) identify key knowledge and implementation gaps that must be addressed to position RA as a cornerstone of future farming.

Concept and Principles of Regenerative Agriculture

Although definitions vary, regenerative agriculture is generally described as a set of principles and practices that aim to restore and enhance ecosystem functions, especially soil health and biodiversity, while producing food, fibre, and other services. A widely cited synthesis identifies six core principles: (1) minimize soil disturbance, (2) maintain permanent soil cover, (3) keep living roots in the soil year-round, (4) maximize species diversity, (5) integrate livestock appropriately, and (6) manage inputs and waste using circular economy principles, limiting, or eliminating synthetic agrochemicals where feasible (Khangura *et al.*, 2023). RA overlaps substantially with conservation agriculture, agroecology, and organic farming, but places an explicit emphasis on measuring and improving regenerative outcomes, especially SOC sequestration, soil biological activity, and system resilience (Colombi *et al.*, 2025). Regenerative Organic Agriculture (ROAg), for example, extends organic standards with additional requirements on soil regeneration, animal welfare, and social fairness. Critiques note that the term "regenerative" is sometimes used loosely in marketing without rigorous metrics, suggesting a need for clearer, outcome-based definitions and standardized indicators of soil health, carbon gains, and biodiversity.

Core Regenerative Practices

Conservation tillage and no-till

Reducing soil disturbance through reduced tillage (RT) and no-till (NT) is a foundational practice in RA. A recent meta-analysis from Northeast China synthesizing 527 observations from 140 studies found that conservation tillage increased SOC stocks by 4.2% on average and crop yield by 2.7%, with NT showing the largest SOC gains (+5.9%) (Huang *et al.*, 2025). Similar trends are reported in many places, though yield responses can vary with climate, soil texture, and residue management (Pramanick *et al.*, 2024; Kar *et al.*, 2021)

Cover crops, diversified rotations, and intercropping

Cover crops and diversified rotations enhance ground cover, nutrient cycling, and biological diversity. A recent global meta-analysis in corn production systems estimated that cover crops are currently sequestering about 5.5 million Mg SOC per year in the United States and could sequester up to 175 million Mg SOC per year globally under wider adoption. Intercropping and green manures, combined with reduced tillage, further improve rooting depth, nutrient capture, and weed suppression (Moisés *et al.*, 2025).

Organic amendments and regenerative organic systems

Regenerative systems typically rely on organic amendments such as compost, farmyard manure, green manures, and bio-fertilizers, which supply nutrients while building SOC and microbial biomass. Colombi and colleagues (2025) synthesize evidence showing that regenerative organic systems can accumulate new SOC at rates of 0.3–1.5 t C ha^{-1} yr^{-1}, depending on climate, soil type, and management, while often improving soil structure, water-holding capacity and nutrient availability.

Integrated crop–livestock systems and agroforestry

Integrating crops with livestock and trees allows nutrient recycling, diversified income, and enhanced system resilience. A global assessment of seven regenerative practices reported that agroforestry and cover cropping on arable and perennial land offer some of the highest soil carbon sequestration potentials among RA practices, particularly when combined with reduced tillage and non-chemical nutrient and pest management. Integrated crop–livestock systems can also reduce reliance on external feed and synthetic fertilizers by utilizing crop residues and manure within the farm.

Biological inputs and reduced synthetic agrochemicals

RA emphasizes substituting synthetic fertilizers and pesticides with biological alternatives such as bio-fertilizers, bio-stimulants, and bio-control agents. In India, the agricultural biological market, closely linked to regenerative and natural farming, is estimated at around USD 16 billion (2024) and projected to grow at over 14% annually, though adoption is constrained by regulatory and awareness barriers. Practices such as Zero Budget Natural Farming (ZBNF) and Community Managed Natural Farming (CMNF) in

Andhra Pradesh focus on on-farm bio-inputs and Soil biota restoration.

Environmental and Agronomic Benefits

Soil health and carbon sequestration

Most RA practices directly target soil health and SOC. Villat and Nicholas (2024) estimated that agroforestry, cover cropping, non-chemical fertilization, and no-till can significantly increase SOC stocks, with agroforestry and cover crops particularly effective in both arable and woody perennial systems. Meta-analyses from different regions show SOC increases of 4–6% under conservation tillage and cover cropping alone (Huang *et al.*, 2025). Improved soil structure and organic matter enhance cation exchange capacity, nutrient retention, and microbial activity, contributing to more stable yields under climatic stress. Sher *et al.* (2024) highlight that RA can reverse soil degradation trends by simultaneously reducing erosion, restoring soil biota, and improving nutrient cycling.

Biodiversity and ecosystem services

RA promotes both above- and below-ground biodiversity. Maintaining diverse crop rotations, cover crops, and perennial vegetation supports beneficial insects, pollinators, and natural enemies of pests, while diversified soil food webs contribute to nutrient cycling and disease suppression. Studies comparing regenerative and conventional corn systems show improved pest regulation and resilience in RA systems, reducing pesticide dependence (Dey *et al.*, 2024).

Water regulation and climate resilience

Enhanced SOC and root systems improve infiltration and water-holding capacity, reducing runoff and drought vulnerability. FAO and ITPS emphasize that degraded soils are more prone to erosion and yield losses of up to 50%, whereas well-structured soils under conservation practices suffer less productivity decline under extreme events. In semi-arid landscapes, agroforestry and RA practices can also moderate microclimate, reduce evapotranspiration, and stabilize yields (Villat and Nicholas, 2024).

Greenhouse gas mitigation and carbon markets

By increasing SOC and reducing reliance on synthetic N fertilizers, RA can mitigate GHG emissions. A recent meta-analysis suggests that organic and regenerative fertilization strategies can reduce N_2O and CH_4 emissions by about 0.8–2.3% relative to conventional management, with larger mitigation potential when combined with cover crops and reduced tillage. Given that agrifood systems account for roughly 32% of global GHG emissions, such improvements are significant at scale (FAO, 2025). Emerging soil carbon markets are increasingly linked to RA. One industry analysis notes the issuance of nearly 0.3 Mt CO_2-eq of soil credits from a single 0.55 million ha project, illustrating the potential for monetizing regenerative practices. However, robust monitoring, reporting, and verification (MRV) systems are essential to ensure environmental integrity.

Socio-Economic and Policy Dimensions

Farm economics and livelihood impacts

The economic performance of RA depends on time horizon, commodity prices, and local conditions. A recent cost–benefit analysis in rural settings found that regenerative systems often incur higher initial costs (e.g., for cover-crop seed, fencing, training) but deliver higher net present value over 10–20 years, owing to reduced input expenditure and improved resilience. Industry and NGO evaluations similarly report potential long-term profit increases of 15–25% and long-run profit margins 70–120% higher than baseline in well-managed RA projects. Nevertheless, short-term yield dips and learning costs can discourage adoption, especially among smallholders with limited risk-bearing capacity. Access to credit, extension support, and risk-sharing mechanisms (e.g., insurance, carbon finance) are therefore critical (Sher *et al.*, 2024).

Corporate and market initiatives

Major agrifood corporations are increasingly investing in RA to meet climate and sustainability commitments. For example, McDonald's has announced a USD 200 million initiative over seven years to promote regenerative grazing and wildlife-friendly practices on cattle ranches across up to 4 million acres in the United States, in partnership with the National Fish and Wildlife Foundation. Similar commitments by companies such as General Mills, Nestlé, Walmart, and PepsiCo are helping mainstream RA lending, technical assistance, and procurement standards, though concerns remain about greenwashing and uneven benefit sharing along supply chains (Sher *et al.*, 2024).

Policy support and large-scale public programmes

Public policy is pivotal for scaling RA, particularly in smallholder-dominated regions. The Andhra Pradesh Community Managed Natural Farming (APCNF) programme in India is a leading example of a state-led, community-driven regenerative transition. Initiated as Zero Budget Natural Farming in 2016 and later expanded as APCNF, the programme aims to cover about six million farmers over six to eight million hectares through agro-ecological and regenerative practices, relying heavily on women's self-help groups and community resource persons. Early assessments report improvements in soil health, reduced input costs, and enhanced resilience, though rigorous, long-term evaluations are ongoing. Other policy instruments supportive of RA include payments for ecosystem services, subsidies for cover crops and agroforestry, support for biological inputs, and integration of RA metrics into national climate and land restoration strategies (e.g., India's commitments under the UNCCD to restore 26 million ha of degraded land by 2030).

Challenges, Trade-offs, and Research Gaps

Despite its growing prominence, regenerative agriculture faces multiple challenges that must be addressed for effective large-scale adoption. A central issue is the definitional ambiguity surrounding regenerative agriculture, as widely varying interpretations across studies hinder comparability and risk diluting scientific and policy standards; this underscores the need for consistent, outcome-based metrics such as soil organic carbon (SOC) thresholds, biodiversity indices, and hydrological indicators, along with standardized measurement frameworks. Yield responses to regenerative practices are also highly context-specific: although many long-term studies report stable or improved productivity after the transition period, short-term yield declines are common, especially in high-input systems or water-limited environments, highlighting the importance of optimizing practice bundles for specific agro-ecological and socio-economic settings. A further challenge lies in the significant data gaps from the Global South; most robust measurements of SOC, yield, and greenhouse gas outcomes originate from North America, Europe, and China, while evidence from India, Africa, and other developing regions remains limited, even though emerging regional meta-analyses are beginning to fill this knowledge gap. Socio-economic and institutional constraints, including restricted access to extension services, high transaction costs for carbon market participation, insecure land tenure, and subsidy regimes still favouring conventional inputs, also inhibit adoption, alongside regulatory hurdles for biological inputs and limited farmer awareness. Finally, concerns over co-option and greenwashing persist as private-sector interest in regenerative agriculture accelerates; corporate programmes may focus narrowly on carbon credit generation while neglecting equity, biodiversity, and farmer knowledge systems, reinforcing the need for multi-dimensional sustainability indicators and inclusive governance frameworks.

Conclusion

Regenerative agriculture offers a compelling pathway for the future of farming by reversing soil degradation, enhancing biodiversity, mitigating climate change, and strengthening rural livelihoods. Guided by principles such as reduced soil disturbance, continuous soil cover, diversified cropping systems, maintaining living roots, and integrating livestock and trees, regenerative agriculture has demonstrated its ability to increase soil organic carbon, improve water-use efficiency, and stabilize yields under climatic stress, as shown by recent meta-analyses and long-term field studies. However, regenerative agriculture is not a uniform, universally applicable solution; its outcomes vary considerably across regions, depending on biophysical conditions, socio-economic constraints, and the extent to which different practices are integrated coherently. A forward-looking agenda for regenerative agriculture must emphasize scientific rigor and measurable outcomes through long-term, site-specific experiments that track soil carbon, yields, biodiversity, and greenhouse gas emissions, supported by harmonized indicators and robust monitoring, reporting, and verification frameworks. It must also promote farmer-centred innovation by co-designing technologies and practices with smallholders, women farmers, and Indigenous communities, as demonstrated in initiatives such as APCNF and similar participatory programmes. Enabling policies and financial mechanisms are equally important, including reoriented subsidies, improved access to green credit, ecosystem service payments, and carbon finance backed by strong environmental and social safeguards, along with investment in extension systems and digital tools that guide regenerative decision-making. Furthermore, equitable value chains are essential to ensure that farmers benefit fairly from price premiums, sustainability certifications, and carbon markets, preventing regenerative agriculture from becoming merely a branding exercise for downstream companies. If these scientific, institutional, financial, and market conditions are met, regenerative agriculture can become a transformative force—shifting food systems away from extractive practices and toward more resilient, climate-smart, and socially inclusive models of production, ultimately establishing itself as a key foundation for the future of farming.

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