Regenerative Agriculture: A New Pathway to Restore Soil Health for Sustainable and Climate-Resilient Crop Production

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OPEN ACCESS

Keywords

Regenerative Agriculture, Soil Health, Soil Organic Carbon, Conservation Tillage, Crop Diversification, Climate Resilience

How to cite this article:

Sonam., Saini, A. K. and Meena, M. L. 2026. Regenerative Agriculture: A New Pathway to Restore Soil Health for Sustainable and Climate-Resilient Crop Production. *Vigyan Varta* 7 (11): 147-156.

ABSTRACT

Regenerative agriculture is a sustainable approach to climate-smart crop production that restores soil health, conserves natural resources and enhances agricultural resilience. Practices such as conservation tillage, crop rotation, cover cropping, residue retention, integrated nutrient management, agroforestry and efficient water management improve soil organic carbon, biodiversity, nutrient-use efficiency and water retention. These practices can enhance crop productivity, reduce dependence on synthetic inputs, lower production costs and strengthen resilience to drought, heat stress and erratic rainfall. Integration with precision agriculture, remote sensing and weather-based advisory systems can further improve resource-use efficiency. However, wider adoption requires farmer training, effective extension services and supportive policies. Thus, regenerative agriculture offers a promising pathway towards climate-resilient farming, environmental sustainability, food security and improved farmer livelihoods.

INTRODUCTION:

Agriculture plays a vital role in food security, rural livelihoods and economic development. However, intensive cultivation, excessive tillage, imbalanced fertilizer use, monocropping and improper water management contribute to soil degradation, nutrient depletion, erosion and declining soil biological activity, threatening long-term agricultural sustainability. Regenerative agriculture is an integrated approach that aims to restore soil health, enhance biodiversity, improve nutrient cycling and sustain agricultural productivity (Muhie, 2022). As a comprehensive farming approach, this system seeks to restore and indeed lift the total environment of the farm with an emphasis on soil health. RA's central objective is to improve ecosystem functions while maintaining productive farming systems (Newton *et al.,* 2020). Soil health is fundamental to maintain efficient food production systems and serves as the primary source of nutrients, water, and microbial ecosystems. The increasing global population and climate change are exerting unprecedented pressure on our limited natural resources. In this context, sustaining and enhancing soil fertility is crucial for ensuring long-term food security and agricultural sustainability (Lehman *et al*., 2015).

Major practices include cover cropping, crop rotation, reduced tillage, organic amendments, agroforestry and crop livestock integration when adapted to local climatic and farming conditions, these practices can improve soil organic matter, canned water, reduce erosion and strengthen climate resilience. (Atapattu and Udumann, 2024). However, their effectiveness varies with management practices and environmental conditions. In India, regenerative agriculture offers considerable potential to address soil degradation, water scarcity and the challenges faced by smallholder farmers across different agroclimatic regions.

1. Principles of Regenerative Agriculture

Regenerative agriculture is based on interconnected principles that aim to restore soil functions and improve the sustainability of agricultural ecosystems. Their implementation should be adapted to local farming conditions rather than treated as a rigid, identical package for every farm (Udumann *et al.,* 2025)

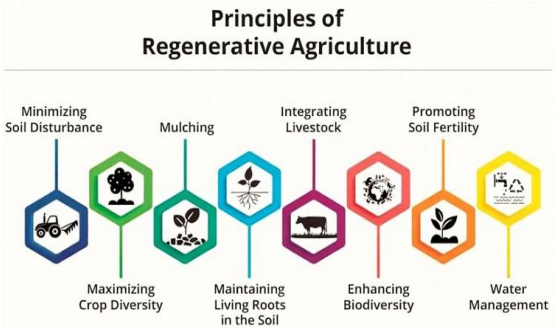


Fig. 1 Core principles of regenerative agriculture

1.1 Soil health improvement

Healthy soil supports plant growth through physical structure, nutrient availability, water regulation and biological activity. Regenerative approaches seek to improve these by maintaining organic matter, reducing disturbance and erosion, enhancing beneficial organisms. Soil health should be evaluated through physical, chemical and biological indicators.

1.2 Biodiversity conservation

Biodiversity includes the diversity of crops, beneficial insects, soil microorganisms, earthworms and other organisms associated with agricultural landscapes animals. Diversified cropping systems provide different habitats and food resources which supports pollination, nutrient cycling and biological pest regulation. It enhances yield stability and

drought tolerance of crops due to the differences in the rotations which enhances soil health (Gaudin *et al.,* 2015).

1.3 Minimum soil disturbance

Excessive tillage can disrupt soil aggregates and structure, accelerate the decomposition of organic matter and increase erosion risks. Minimum or zero tillage can protect soil structure and conserve moisture. However, tillage decisions should consider soil compaction, drainage, weed pressure, available machinery and the requirements of crop. No-till methods can increase soil organic carbon (SOC) by 9.9%, and together with crop residue return and rotation, can raise SOC to 12.77%, improving soil quality and addressing food insecurity and adverse climatic conditions (Chew *et al.,* 2024).

1.4 Permanent soil cover

Maintaining soil cover with crop residues, mulch or living cover crops protects the soil surface from raindrop impact, reduces evaporation and limits erosion. Residues also provide carbon substrates for soil organisms as they decompose and helps prevent soil erosion and they also offer homes for soil microorganisms (Somasundaram *et al.,* 2020).

1.5 Crop diversity and rotation

Crop rotation and intercropping can improve nutrient use, structure of soil, organic content, quantity and quality of microorganisms. It provides different rooting patterns, reduce the buildup of certain pests and diseases, and spread production risks across crops with different environment requirements (Atapattu and Udumann, 2024).

1.6 Continuous living roots

Maintaining living root throughout the year by suitable cover crops or perennial vegetation can support soil organisms and improve the capture of nutrients that might otherwise be lost. These roots release organic compounds to the rhizosphere for supporting microbial population and functioning, which improves nutrient cycling and soil structure, while roots and their residues contribute to soil aggregation and organic matter formation.

1.7 Integration of livestock

Crop–livestock integration can recycle nutrients through manure, diversify farm income and improve the use of forage and crop by-products. Extension grazing practices such as intensity, duration and stocking density, discrete grazing, adaptive rotational or multiple-paddock grazing improve the health of the soil by promoting plant growth, soil organic matter and water infiltration.

1.8 Efficient Water Management

Improving infiltration, conserving soil moisture and reducing losses through suitable soil-cover and water-management practices. Small-scale water harvesting strategy is feasible in assisting developing countries to cope with the future adverse effects of climate change on water resources. Scheduling irrigation can save water by 20–40% without loss of production (Qiao *et al.* 2019)

2. Major Regenerative Agricultural Practices

2.1 Mulching and Cover cropping

Cover cropping and mulching improve soil health by increasing soil organic carbon (SOC), conserving moisture, reducing erosion and suppressing weeds. Legumes such as sun hemp and cowpea enhance nitrogen availability through biological nitrogen fixation, while crop residues improve nutrient cycling. In dryland areas, species selection, timely termination and partial residue retention help minimise moisture competition and maintain soil cover, especially where residues

are used as livestock feed and fuel (Prem *et al.,* 2020).

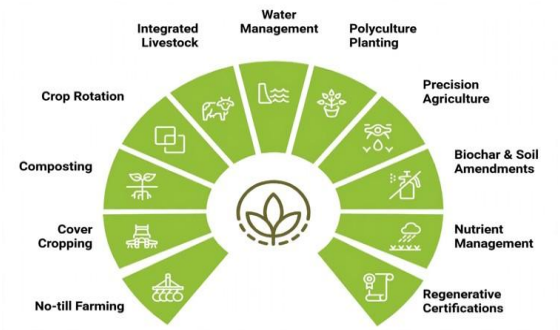


Fig.2 Practices of regenerative agriculture

2.2 Crop rotation

Crop rotation involves growing different crops sequentially on the same field to improve soil fertility and productivity. Including legumes enhances nitrogen availability, while different crops improve nutrient use and help manage weeds, pests and diseases. Its effectiveness depends on crop selection, residue management and local conditions (Bender *et al.,* 2016).

2.3 Conservation and reduced tillage

Conservation tillage minimises soil disturbance through zero and minimum tillage. It helps preserve soil structure and moisture, reduce erosion, fuel and labour costs. However, its effectiveness depends on soil conditions, management practices and weed control. Soil carbon changes should be assessed throughout the soil profile to determine long-term benefits (Lal, 2020).

2.4 Compost and farmyard manure application

Compost and farmyard manure are important organic amendments that improve soil fertility, supply nutrients and enhance soil biological activity. Their nutrient content varies with composition, decomposition and storage; therefore, application should be guided by soil testing and crop nutrient requirements. Proper handling is essential to prevent contamination and nutrient losses.

2.5 Green manuring and Agroforestry

Green manuring and agroforestry are important regenerative practices that improve soil fertility, enhance biodiversity and support sustainable crop production. Leguminous green-manure crops such as sun hemp (*Crotalaria juncea*) and dhaincha (*Sesbania spp*.) add nitrogen and organic matter, while agroforestry integrates trees with crops to provide leaf litter, reduce wind erosion and recycle nutrients. Their effectiveness depends on suitable species selection, moisture availability, biomass production, tree spacing and proper management to minimise competition for light, water and nutrients (Bodner *et al.,* 2021).

2.6 Integrated nutrient management

Integrated nutrient management combines organic nutrient sources, biological nutrient inputs and mineral fertilizers needed to meet crop requirements. Its objective is to sustain soil fertility while improving nutrient-use efficiency and minimizing nutrient losses

2.7 Biological and integrated pest management

Biological pest management includes natural enemies, microbial agents and other biological processes to manage pests. Integrated pest management combines biological control with crop rotation, resistant varieties, monitoring, cultural methods and carefully targeted pesticides when necessary. Management should be based on the identity of the pest, the crop's vulnerability and local evidence.

2. Effects of Regenerative Agriculture on Soil Health

Soil health is central to regenerative agriculture because soil properties influence

nutrient supply, water availability, root development and crop performance.

3.1 Soil organic carbon

Soil organic carbon (SOC) improves nutrient cycling, soil structure and water retention. Cover crops, compost, manure and residue retention enhance SOC and its fractions, including microbial biomass and particulate organic carbon. However, carbon accumulation depends on soil type, climate, management practices and experimental duration (Lal, 2020).

3.2 Soil structure and aggregation

Soil aggregates influence porosity, aeration, infiltration and resistance to erosion. Organic residues, roots, fungal hyphae and microbial products can help bind soil particles into aggregates. Reduced disturbance and continuous soil cover may support aggregate stability, although responses depend on soil texture, moisture and management duration.

3.3 Water-holding capacity and infiltration

Organic matter can contribute to water retention, while improved aggregation and root channels can support infiltration. Surface residues also reduce direct evaporation and protect soil from raindrop impact. These improvements may be especially useful in rainfed systems, although their magnitude varies with soil texture, rainfall distribution and the amount of organic material supplied (Qiao *et al*., 2019).

3.4 Nutrient cycling and availability

Organic amendments and crop residues improve nutrient cycling by returning nutrients to the soil through decomposition. Soil microorganisms convert these nutrients into plant-available forms, while legumes contribute nitrogen through biological fixation. However, nutrient availability depends on biomass production, residue quality and decomposition, making soil testing and balanced nutrient management essential for sustainable crop production.

3.5 Soil microbial activity and biodiversity

Soil microorganisms participate in decomposition, nutrient transformation, aggregation and interactions with plant roots. Organic amendments and diverse root systems can provide energy and habitat for these organisms. An increase in microbial biomass or diversity does not establish an improvement in every soil function.

3. Effects on Crop Growth and Productivity

Regenerative practices may influence crop growth through changes in soil physical conditions, nutrient supply, water availability and pest pressure.

4.1 Crop establishment and root development

Suitable soil structure, moisture and nutrient availability can promote seedling establishment and root development. Residue-covered fields may conserve moisture, but excessive surface residues can complicate planting where equipment is unsuitable. Crop establishment consequently depends on the interaction between management and field conditions.

4.2 Nutrient availability and crop growth

Organic amendments can provide nutrients and improve soil conditions, while legume rotations may contribute nitrogen. However, organic nutrient release may not coincide with peak crop demand. Balanced nutrient management and appropriate timing are necessary to prevent nutrient deficiencies, especially during the transition from conventional management.

4.3 Crop yield and productivity stability

Regenerative practices do not guarantee higher yields in every crop or season. In a global analysis of cover cropping, increases in soil carbon and crop yield occurred simultaneously in 59.7% of 434 paired observations, demonstrating both the potential for combined benefits and the variability of outcomes. Yield responses depend on initial condition of the soil, water availability, crop species, nutrient inputs and duration of practice adoption.

4.4 Resilience to environmental stresses

Improved soil cover, water infiltration and organic matter can help farming systems cope with some drought and heavy-rainfall conditions. Crop diversification can also distribute risk across species with different growth cycles and environmental requirements. However, regenerative agriculture cannot eliminate the effects of severe droughts, floods, heat waves or major pest outbreaks. Its contribution to resilience should be evaluated using long-term yield variability, soil-water measurements and farm-level economic outcomes.

5. Environmental Benefits of Regenerative Agriculture

5.1 Carbon sequestration and climate-change mitigation

Regenerative practices can increase carbon inputs to soil and, under suitable conditions, improve soil-carbon storage. Cover crops, agroforestry, organic amendments and residue retention are particularly relevant because they increase the supply of plant-derived carbon to agricultural systems. The overall climate benefit must also account for greenhouse gas emissions associated with fertilizer use, manure, fuel consumption and other farm operations (Lal, 2020).

5.2 Water conservation

Mulching, improved soil structure, organic matter management can help reduce evaporation, improve infiltration and support soil-water storage. These effects may increase the effectiveness of rainfall, particularly in water-limited environments. However, cover crops can consume water before the main crop is established, so species choice and termination timing are important in dry regions.

5.3 Erosion control

Crop residues, living vegetation and improved soil aggregation protect the soil surface from wind and water erosion. Reducing erosion helps retain fertile topsoil and reduces the movement of sediment and associated nutrients into nearby water bodies. These benefits depend on the amount of ground cover, slope, rainfall intensity and the management of field boundaries.

5.4 Biodiversity enhancement

Crop diversification, agroforestry, flowering cover crops and reduced disturbance can provide habitats and food resources for beneficial insects and soil organisms. These changes may support pollination, biological pest control and nutrient cycling.

5.5 Reduced nutrient losses and pollution

Improved nutrient management can reduce nutrient losses through runoff, erosion and leaching. Organic amendments and cover crops may capture nutrients that would otherwise be lost, while integrated pest management can reduce unnecessary pesticide applications. Nevertheless, excessive manure or fertilizer application can still cause pollution, even in systems described as regenerative.

6. Challenges and Limitations

Regenerative agriculture offers several environmental and soil-health benefits, but its adoption may be limited by economic, technical, climatic and institutional challenges.

1. Transition costs: Farmers may need to invest in new equipment, seeds, training and organic inputs before benefits become noticeable.

2. Limited biomass availability: In dry regions, crop residues are often needed for livestock feed and fuel, while cover crops may compete with the main crop for water.

3. Nutrient-management difficulties: Organic inputs vary in nutrient content and release rates, which may cause nutrient deficiencies or poor synchronisation with crop demand.

4. Weed, pest and disease pressure: Reduced tillage and residue retention can alter weed growth and pest habitats, requiring crop rotation and integrated management.

5. Variable yield responses: Crop yields may increase, remain stable or decline depending on soil type, climate, crop species and management practices.

6. Limited region-specific evidence: Practices successful in temperate regions may not perform similarly under tropical, semi-arid or irrigated Indian conditions, highlighting the need for local field trials.

7. Market and institutional constraints: Limited access to machinery, quality seeds, credit, technical guidance and reliable markets can discourage farmers from adopting regenerative practices.

7. Relevance to Indian Agriculture

India's agricultural systems are highly diverse, and regenerative practices need to be adapted to regional rainfall, soil type, cropping intensity, farm size and livestock integration.

7.1 Rainfed agriculture

Rainfed farming areas face irregular rainfall, moisture stress and erosion risks. Residue retention, suitable cover crops, crop rotations, contour-based soil conservation and organic matter management can help conserve soil and water.

7.2 Smallholder farming systems

Smallholders may benefit from low-cost practices such as crop diversification, compost, green manuring and partial residue retention. Community-level machinery services, farmer groups and extension support can reduce the cost of adopting practices that require specialised equipment.

7.3 Soil degradation and declining organic matter

Where soil organic matter is low, the combination of organic inputs, residue management, appropriate tillage and diversified cropping may help restore soil functions. A recent India-focused meta-analysis synthesising 147 peer-reviewed studies reported that the effects of regenerative practices on soil organic carbon varied with practice, duration and agroclimatic region (Patil *et al*., 2025).

7.4 Water scarcity

In water-limited regions, soil-cover practices and suitable crop rotations may improve water conservation. Farmers should consider whether a cover crop is likely to use water needed by the following crop. In irrigated systems, improved irrigation scheduling and nutrient management should complement soil-restoration practices.

7.5 Crop–livestock integration

Livestock can provide manure and help recycle nutrients, while crop residues can contribute to animal feeding. However, the competing uses of residues must be considered when planning soil cover. Manure should be composted, stored and applied appropriately to reduce nutrient losses and sanitation risks.

8. How to Implement Regenerative Practices

1. **Assess Soil Health:** Test soil organic matter, nutrients, compaction and biological activity; identify field variability.
2. **Start Small:** Introduce cover crops, reduced tillage or mulching in a small area and observe the results.
3. **Plan Crop Rotations and Grazing:** Select suitable crops and manage grazing according to soil fertility, forage recovery and local climate.
4. **Invest Strategically:** Purchase or rent suitable machinery, use locally available inputs and explore financial assistance where eligible.
5. **Monitor and Adapt:** Track soil health, crop yields, input costs and profitability; modify practices according to observed results.

9. Research Gaps and Future Prospects

9.1 Long-term field experiments: Long-term studies are needed to assess changes in soil health, organic carbon, crop productivity and farm profitability under regenerative practices.

9.2 Soil-carbon measurement: Standardised methods are required to measure soil-carbon stocks, their long-term stability and associated greenhouse gas emissions. New digital platforms will allow farmers to track soil carbon levels and participate in carbon markets, turning sequestration into a revenue stream.

9.3 Economic assessment: Studies should evaluate adoption costs, labour requirements, profitability and economic risks, particularly for smallholder farmers.

9.4 Region and Crop-specific practices: Location-specific research is essential to develop effective regenerative strategies for rainfed and semi-arid areas and different crops, cropping systems and agroclimatic conditions.

9.5 Digital agriculture and extension services: Soil testing, remote sensing and farmer training can support the monitoring, adoption and effective implementation of regenerative practices. IoT sensors, drones, and AI-driven analytics provide real-time insight into soil moisture, nutrient availability, and crop health, enabling precise, site-specific management.

CONCLUSION

Regenerative agriculture offers a promising approach to improving soil health, conserving natural resources and supporting resilient agricultural production. Practices such as crop rotation, cover cropping, reduced to and organic nutrient management can enhance soil fertility, water conservation and climate resilience. In India, these practices offer potential benefits for rainfed and smallholder farming systems. However, their effectiveness depends on local conditions, proper management and long-term evaluation. Therefore, region-specific research and farmer support are essential for achieving sustainable agricultural productivity and environmental conservation.

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