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REVIEW ARTICLE

Regenerative agriculture for sustainable crop productivity: A comprehensive review

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Abstract

Regenerative agriculture is a promising approach that addresses the challenges posed by conventional farming methods, which often lead to soil degradation and reduced productivity over time. The goal of regenerative agriculture is to revitalise the soil and landscape, providing environmental, economic and social benefits to communities. Core principles include prioritising soil health and carbon sequestration by maintaining soil cover, minimising disturbance, sustaining living roots year-round, fostering diversity, incorporating livestock and reducing synthetic inputs such as herbicides and fertilisers. The implementation of crop diversification and rotation techniques is a key strategy in regenerative agriculture. These techniques promote the cycling of nutrients into the soil and enhance the diversity of soil microorganisms such as bacteria. Agroforestry, another component of regenerative agriculture, contributes to carbon sequestration by utilizing stable, deep-rooted systems and storing carbon within plant biomass. However, the overall efficacy of these methods may vary in different environments. Potential limitations include the upper thresholds for carbon sequestration and increased nitrogen demand. Although there are challenges to be addressed, regenerative agriculture shows promise in improving soil quality, crop productivity and overall farm economics. This represents a shift towards more sustainable and resilient farming practices that could benefit the environment and communities.

Keywords: cover crops; GHG emissions; microbial load; soil health; sustainability

Introduction

The global food system is a significant contributor to anthropogenic emissions, accounting for approximately 25 % of annual emissions. Additionally, it plays a role in terrestrial acidification, accounting for nearly one-third of the total impact and is a major factor in the global eutrophication of surface waters (1). This is achieved through the use of synthetic pesticides, artificial fertilizers, fossil fuels and intensive food production methods, including crop cultivation, livestock farming and aquaculture (2). The central challenge facing humanity is to ensure the production of adequate, safe and nutritious food for a growing and prosperous global population while staying within ecological boundaries (3). The significance of food production within a planet's carrying capacity is increasingly recognized in various policies and initiatives. Notable examples include the EU Circular Economy Action Plan and the Paris Climate Agreement. This growing awareness has driven the evolution of new agricultural paradigms. Some of these narratives emphasize production-oriented approaches, such as sustainable intensification, which seeks to increase yields while minimizing environmental harm (3). An alternative perspective suggests that relying solely on production-oriented solutions is inadequate for addressing humanity's central challenge. According to this viewpoint, adjusting consumption patterns is essential for the global food system to function sustainably within Earth's ecological limits (4). Combining production and consumption-oriented approaches by integrating these perspectives. They highlighted the importance of achieving a balance with the ecological environment (5).

Their perspective takes a food systems approach, emphasizing the preservation of natural resources by closing the nutrient and carbon cycles within the food system. This concept is often referred to as the circular food system. Various farming approaches within these narratives have shared objectives, including achieving global food security, reducing dependence on external inputs and mitigating environmental impacts. Some of these approaches are well-defined in the scientific literature and are subject to regulations such as organic agriculture, climate-smart agriculture and sustainable intensification For instance, the International Federation of Organic Agriculture Movements (IFOAM) and the Food and Agriculture Organization (FAO) set global standards for organic agriculture, while the Agricultural and Processed Food Products Export Development Authority (APEDA) oversees related regulations at the national level (6). Some of these farming approaches are well-established concepts, whereas others, such as circular agriculture, remain primarily theoretical and scientific. Regenerative agriculture, which has recently emerged as a solution for sustainable food systems, has received increasing attention in the literature (7).

This approach focuses on strengthening and rejuvenating robust systems powered by effective ecosystem processes and fertile organic soil. These systems can provide a wide range of ecosystem benefits including soil carbon sequestration and enhanced soil water retention (8). In particular, regenerative agriculture seeks to minimize or eliminate external inputs, such as chemicals, while restoring soil health, biodiversity and ecosystem functions. It aims to enhance productivity and promote environmental stewardship simultaneously (9).

Regenerative agriculture is crucial due to its commitment to sustainability, employing methods such as recycling water and nutrients while prioritising thepreservation. of soil health Research has shown that regenerative agriculture can mitigate the depletion of natural resources, resulting in enhanced ecosystem services and economic benefits for local communities (10, 11). By 2022, the global market for regenerative agriculture was valued at USD 975.2 million. From 2023 to 2030, a compound annual growth rate (CAGR) of 15.9 % is anticipated, with the total surpassing USD 4290.9 million by 2032. North American countries, including the United States, Canada and Mexico, held the largest share of the regenerative agriculture market in 2022, accounting for 37 %. Other key players in this sector include Western European nations, such as the United Kingdom, Germany and France, as well as Asia-Pacific countries, including India, China and Australia (12). Increasing dissatisfaction with contemporary industrial farming practices and their resulting environmental and societal harms is paving the way for the greater acceptance of alternative approaches, such as regenerative agriculture (13, 14).

Background and perspective: The flourishing of regenerative agriculture

Regenerative agriculture, a term first popularised by Allan Savoury in 1979, has been in use since the 1970s (8). Since the late 1970s, "regenerative agriculture" and "regenerative farming" have been associated with the term "regenerative," but it was in the early 1980s, mainly through the Rodale Institute's efforts, known for publications such as Organic Gardening and Farming, that gained broader recognition, significantly advancing the organic farming movement. It also enhances land and soil biology, boosts productivity and promotes economic stability with minimal environmental impact, emphasizing the production of biocide-free food and increasing agricultural participation while reducing reliance on non-renewable resources (15).

In 1983, Richard Harwood, a leading figure in the global farming systems research movement, authored a comprehensive analysis of regenerative agriculture during his tenure as Director of the Rodale Research Centre. His work further solidified the global understanding and implementation of regenerative practices, marking a pivotal moment in the rise of regenerative agriculture as a sustainable farming approach. Furthermore, more research is essential to comprehend the rise of regenerative agriculture, its integration with other agricultural narratives and the broader social-ecological forces driving it, illuminating its potential contribution to restructuring the agri-food system (16).

Augmentations of regenerative agriculture

Regenerative agriculture harnesses natural processes to enhance biological activity, enhance soil health, optimize nutrient cycling and restore ecosystem functionality. Its goal is to produce food and fiber while also maintaining or enhancing profitability (17, 18). Additionally, it captures carbon in the soil and biomass, thereby countering climate change and atmospheric carbon accumulation. It also increases yields, resilience to climate instability and enhances the health and vitality of farming and ranching communities (18). Regenerative agricultural methods aim to revitalize land after cultivation, yet their widespread adoption is in its early stages, spurred by crises and the pursuit of alternative farming techniques to address agricultural challenges (13).

Regenerative agriculture places a strong emphasis on biological approaches to improve soil fertility. It holds promise as a solution to regional agricultural challenges and offers opportunities for climate change adaptation, potentially leading to mitigation benefits (19)**.** It represents a holistic farming approach that emulates natural systems, prioritizes soil health, enhances biodiversity and aims to deliver environmental benefits while improving ecosystem functionality, farmer well-being, profitability and food security (20, 21).

Regenerative agriculture offers numerous opportunities for farmers to integrate local organic waste, including crop residues, animal manure, composted food waste and green manure, into their agronomic management practices. It combines practices for environmental stewardship, crucial to a sustainable food future and long–term security, evolving over three decades in response to societal concerns over the impacts of industrial agriculture on climate, soil and biodiversity (2, 14). The primary objective is to enhance soil and ecosystem health while simultaneously benefiting the livelihoods of farmers and the broader community. Regenerative agriculture holds promise for addressing various Sustainable Development Goals, such as zero hunger (Goal 2), climate action (Goal 13), life on land (Goal 1 5) and responsible consumption and production (Goal 12), related to environmental sustainability and social equity (22). Regenerative agriculture offers a sustainable approach to meeting the growing demand for food and energy. It reduces energy use by limiting dependence on synthetic fertilizers and pesticides. Instead, it relies on natural methods such as composting and cover cropping to improve soil health and reduces energy (23).

Principles and practices of regenerative agriculture

Regenerative farming systems aim to enhance soil quality and biodiversity on agricultural lands while also ensuring the profitable production of farm goods. Key principles shared among regenerative farming systems are shown in Fig. 1.

It comprises a system of farming practices aimed to rehabilitating and enhancing the entire ecosystem of the farm. This approach focuses on building soil health, improving biodiversity and creating more sustainable agricultural systems. Table 1 provides a summary of the definitions of the practices commonly regarded as part of regenerative agriculture (24-28).

Minimum soil disturbance

Regenerative agriculture enhances soil health by minimizing mechanical disruption through minimal tillage or direct drilling, thereby avoiding the need for extensive ploughing. These practices help to reduce soil erosion, enhance soil structure and improve water drainage (29). By reducing soil disturbance, farmers also slow down the microbial degradation of carbon inputs, potentially increasing the soil's organic content (30). However, the relationship between tillage and soil carbon content is debated. Evidence suggests that no-tillage practices might only redistribute carbon within the soil profile, instead of resulting in an overall increase in soil organic content. Organic inputs and cover cropping are believed to be the primary drivers of soil carbon gains rather than tillage practices themselves (31). Additionally, research indicates that tillage causes only temporary carbon losses compared to the long-term effects observed in no–tillage systems. Reduced or no-tillage practices may also result in increased soil nitrous oxide emissions under waterlogged conditions and the build-up of weeds. Regenerative agriculture promotes soil health by minimizing chemical disruption through reduced pesticide use, although reduced tillage may increase reliance on herbicides (32).

Conservation tillage: In northern Europe, although inversion tillage generally facilitates autumn rainfall infiltration, it can cause runoff due to soil compaction or capping. In contrast, conservation tillage in the USA has been shown to reduce runoff by 15-89 %, along with reducing dissolved pesticides, nutrients and sediments. In the United States, where corn and soybeans are key crops, approximately 30 % of corn and 35 % of soybeans are cultivated using conservation tillage methods, ensuring that at least 30 % of residue remains after planting (33). Conservation tillage is defined as a seedbed preparation technique that prioritizes the retention of residue mulch on the soil surface and the promotion of surface roughness, both of which are deemed pivotal factors.

Long–term trials have revealed that conservation tillage promotes the growth of rhizosphere bacteria, including *Agrobacterium* and *Pseudomonas*. Specifically, in sandy loam soils, this enhances nitrogen fixation and nodulation in pea plants. Studies in the USA have shown that conservation tillage can reduce runoff and sediment losses by 64 % and 99%, respectively and decrease pesticide contamination in surface water (34).

No till and Minimum tillage: A small amount of healthy soil contains a microbial population that exceeds the global human population, which is crucial for soil structure and health (8). Minimising soil disturbance through low-or no-till practices preserves soil structure, boosts organic matter and enhances environmental resilience, while reducing reliance on synthetic inputs (35). A global meta-analysis revealed that no-tillage practices increased carbon stock in the upper 0-30 cm of soil by approximately 4.6 mg per hectare (ranging from 0.78 to 8.43

Table 1. Different definitions of regenerative agriculture practices

S. No	Practices	Definitions	References
1.	**Reduced or no till**	Reducing soil tillage in crop management to prevent soil compaction and the formation of plow–pans.	(24)
2.	**Crop rotation**	Cycling between different crops in different seasons.	(8)
3.	**Cover cropping**	Crops grown to replace bare fallow between growth cycles of the main crop (e.g. in winter), typically ploughed under as green manure.	(25)
4.	**Perennials and Agroforestry**	Integration of cultivated perennials (multi–annual plants), including trees in the case of agroforestry	(26)
5.	**Managed grazing**	Use of regenerative ranching practices e.g. rotational grazing, adaptive multi–paddock grazing, or holistic planned grazing	(27)
6.	**Crop–livestock integration**	Use of Integrated Crop–Livestock (ICL)systems, with or without agroforestry (silvopasture).	(28)

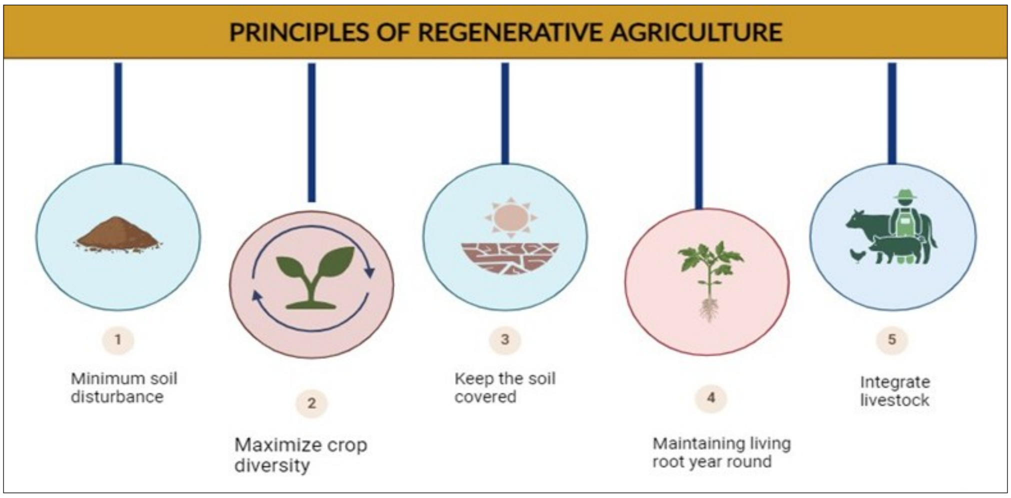

Fig. 1. Principles of regenerative agriculture.

mg/ha, 95 % confidence interval) over 10 years or more, while no significant changes were observed across the entire soil profile (36).

No-tillage practices reduced the global warming potential at acidic soil sites; increased barley yields by 49 % and showed the potential to reduce greenhouse gas emissions in dry climates compared to conventional tillage. Owing to its capacity to address climate change and enhance crop yields, no–tillage is suggested as a valuable climate-smart agricultural practice (37). The long–term implementation of cover crops - particularly vetch - in combination with no–till practices has been found to improve soil properties, including aggregation and moisture retention, especially under dry conditions (38). In the central wheatbelt of Western Australia, a seven-year study conducted on deep sands revealed that various tillage methods showed no discernible effects on crop yields. However, there was an observed increase in soil carbon and microbial activity under no-till treatments, specifically within the top 0.10 and 0.05 m of soil, respectively. When employing no-till instead of conventional tillage, there was an increase in yield by 47 % and 28 %, with or without the application of N and Zn fertilizers, respectively (39).

Maximum crop diversity

Biodiversity indicators, including plant diversity, habitat quality and pollinator abundance, enable the assessment of conservation efforts and enhancement of ecosystem services within mixed crop-livestock regenerative systems. Strategies for diversifying crops, particularly by incorporating legumes, have been shown to reduce reliance on fertilizers, enhance pest control, increase biodiversity and improve soil health (40).

Proponents of regenerative agriculture have moved away from monoculture by increasing crop variety and diversifying plant species in cover crops. This fosters natural pest control and soil fertility, thereby reducing reliance on chemical interventions. Intensive agricultural practices rely heavily on synthetic inputs for maintaining fertility and controlling pests. In contrast, legume crops enhance soil nitrogen levels, offering a cost-effective and environmentally friendly alternative, though they may increase the risk of nitrate leaching into groundwater if not properly managed (41). Notably, in specific contexts, fertilizer application can stimulate plant growth, enhance vegetation cover and subsequently increase soil organic content. Efforts aimed at enhancing biodiversity on non–agricultural land, such as seeding wildflowers or birds or pollinator mixes, implementing agroforestry practices and preserving or establishing hedgerows, also aligning with this diversification principle (42).

Cover crops and crop rotation: A cover crop is defined as planted between cash crop seasons or phases without being harvested directly for income (43). Varied crop rotation is essential not only for maximizing crop yields but also for enhancing soil health. This is achieved by boosting soil fertility, enhancing nutrient efficiency and mitigating the spread of soil–borne diseases. Regenerative agriculture maintains soil cover through plant residues and cover crops, which helps prevent erosion, regulate soil temperature and support beneficial microorganisms. Additionally, practices such as crop rotation and strategic cover cropping improve soil organic matter, enhance nutrient diversity and reduce the incidence of pests and diseases (35).

Crop rotation is a fundamental aspect of agricultural regenerative management. However, in rainfed systems, achieving adequate crop diversity proves challenging due to constraints such as limited cash crop options dictated by soil, climate, or markets, which is especially evident in commercial rainfed field cropping. Diversifying cropping systems has emerged as a crucial management strategy to ensure sustainability (44). Soybeans are considered a pivotal crop within the tillage management region of the Southern Corn Belt. In 1990, over 80 % of soybean cultivation in this area involved rotation with corn, with 58 % following soybean–corn-soybean rotation. A mere 4 % was left unrotated, while 3 % was cultivated after a period of fallow (45).

Multi-species cover crops, including legumes, are thought to improve various ecosystem functions. These functions include biological nitrogen fixation, microbial diversity, reduction in soil compaction, attraction of beneficial insects, weed suppression, regulation of soil temperature and enhanced water infiltration. In addition to improving soil fertility, cover crops also contribute to carbon sequestration. Their widespread adoption could potentially reduce agricultural greenhouse gas emissions by 10 %, comparable to the impact of employing no–till or other alternative cropping methods (46). In a recent meta-analysis, it was discovered that integrating cover crops into crop rotations substantially enhanced soil organic carbon levels. Fine-textured soils exhibited the most significant enhancement, with shallower soil layers (30 cm) experiencing a greater increase than deeper subsurface layers (>30 cm) (47).

Agroforestry: Agroforestry integrates livestock, trees, herbs and shrubs to enhance soil fertility and prevent erosion in alignment with regenerative agriculture principles. It fosters food security through environmental, economic and social benefits, focusing on soil health, biodiversity and carbon sequestration (48, 49). Agroforestry can contribute to regenerative agriculture by developing sustainable systems, such as edible forest gardens and silvopasture, as studied in Sweden for transitioning towards sustainable practices. Agroforestry, particularly in coconut farming, supports regenerative agriculture principles by enhancing biodiversity, soil vitality and carbon storage, thereby serving as a pivotal element in regenerative agricultural methods (50). In Rajasthan, agroforestry and agro-silvopastoral systems showed higher microbial diversity rates than monoculture, as the integration of trees creates favourable conditions for soil microflora (51).

Implementing jackfruit–based agroforestry in Bangladesh resulted in a decreased soil temperature (ranging from 3.37 % to 9.25 %), elevated soil moisture levels (increasing by 10 % to 20 %) and higher concentrations of total nitrogen (with an increase of 9 % to 19 %). These findings suggest a potential enhancement in soil fertility due to improvements in both physical and chemical soil attributes (52). The effects of different agroforestry systems on soil fertility. They observed that systems combining mixed trees with coffee plants, as well as Cordia Africana with coffee plants, demonstrated elevated levels of nitrogen (ranging from 0.17 % to 0.26 %), soil phosphorus, potassium, soil organic carbon and organic matter (53). The literature reports significant yield increases of

150 % and 73 % for maize and sorghum, respectively, under the tree canopy of *Faidhetbia albida* compared to open cropping, attributed to improved microclimate and buffering action. Agroforestry systems exhibit 75 % higher infiltration rates and 57 % lower runoff rates than crop monocultures (54).

Crop residue management

Regenerative agriculture emphasises enhancing the soil ecosystem through year-round soil cover with cover crops and plant residues, which are crucial for maintaining soil health. In pasture systems, avoiding overgrazing is crucial to leaving sufficient plant residues, fostering regrowth and sustaining ecosystem vitality. Regenerative agriculture employs mob grazing, rotating livestock through small paddocks with short grazing periods and long rest periods, thereby enhancing soil health through high stocking densities that promote forage trampling and decomposition. This approach also fosters a nutrient-rich layer of plant residue on the soil surface (55). The goal was to stabilize soil temperature and moisture fluctuations to support the soil microbial community.

Additionally, increasing plant residue inputs to the soil may potentially boost soil carbon levels. In arable systems, farmers can maintain plant residue and cover by leaving crop residues on the soil, planting overwinter cover crops, or sowing or intercropping with companion crops, such as clover. These practices increase carbon input into the soil in the short term (19).

Mulches: Mulches can reduce water runoff, enhance soil infiltration, control weed growth through shading and act as a barrier to evapotranspiration. In regenerative agriculture, mulches have been shown to enhance crop production by minimizing soil erosion, improving water infiltration, retaining soil moisture, suppressing weeds and fostering biodiversity. Common organic mulches include straw, husks, grass, cover crops (used as live mulch), sawdust compost and manure. Globally, polyethylene plastic is the most used inorganic mulch (56). Plastic mulching has gained widespread popularity in agriculture, with its global application exceeding 22 million hectares of cultivated land by 1999 (57). By 2002, its usage had extended to 15 million hectares in China. Each year, approximately 700000 tons of plastic sheeting is employed worldwide for mulching purposes, with the USA alone accounting for 140000 tons (58). Black plastic mulch is the preferred choice for agricultural applications worldwide (59). Using straw as mulch resulted in a 43 % reduction in runoff. Mulches contribute to decreased supplemental irrigation by retaining water, consequently reducing soil profile runoff (60).

Incorporating mulched winter cover crops can boost soil nitrogen levels and enhance organic carbon content (61).The method and timing of cover crop termination require careful consideration to prevent the resurgence of cover crop species as volunteer weeds and to ensure sufficient decomposition of cover crop residue before planting the next crop. In the Mediterranean region, non-chemical termination using a roller crimper can be successfully employed (44).

Maintaining living root year round

Plant roots release photosynthetic sugars, such as glucose, fructose and sucrose, into the soil, nourishing the microbial community and increasing carbon inputs, thereby enhancing carbon sequestration levels. This process is fundamental to boosting soil health and mitigating climate change (62). Maintaining living roots throughout the year improves soil fertility by boosting nutrient availability for subsequent plant growth. It also enhances the soil structure, promoting better aeration, drainage and water infiltration capabilities. Strategies for preserving live roots in the soil include integrating cover crops during winter in crop rotations and allowing pastures to rest with ample residual heights rather than overgrazing, particularly during winter (63).

Integration of livestock

Regenerative agriculture is a farming approach that places significant emphasis on enhancing soil health, with livestock playing a crucial role in this system. Practices such as rotational grazing can boost grass production and foster carbon sequestration in rangelands. However, the extent to which regenerative agriculture is adopted depends on factors such as the guiding principles followed (e.g., promoting biodiversity, reducing soil disturbance), the specific practices employed and the economic viability, environmental and social outcomes.

Rotational grazing and livestock productivity are crucial metrics for assessing the effectiveness of mixed crop–livestock systems. They act as key indicators for evaluating regenerative agricultural practices, enabling the necessary adjustments for optimal performance. A study conducted in Southern Australia found that rotational grazing had a minimal impact on soil organic carbon (SOC) levels. However, rotational grazing of pastures resulted in a 25 % increase in soil organic carbon (SOC) levels within the 0-40 cm layer compared with no–till fields (64). In semiarid rangelands, grazing management can gradually elevate soil carbon levels, averaging an annual increase of 160 kg C ha^{-1}. This is likely attributable to the promotion of perennial grasses characterized by high root-to-shoot ratios. Grasses such as Buffalo grass (B*outeloua dactyloides*) and Indian grass (Sorghastrum nutans) stimulate vegetative growth, enhance tillering and rhizome production, facilitate the return of aboveground carbon to the soil as plant litter and dung and augment root carbon exudation. Extended grazing periods in short-gass ecosystems have been associated with a 24 % increase in soil carbon levels (65).

Livestock integration in arable systems with temporary grass and forage crops enhances soil carbon stocks while mitigating yield reductions through sustainable practices. Introducing additional livestock into arable systems may increase emissions from ruminant enteric fermentation, potentially offsetting the benefits of soil carbon sequestration. However, integrated systems can yield environmental benefits with risk mitigation measures (19). The involvement of livestock, particularly ruminants such as sheep and cattle, in the food system has ignited considerable discussion (66). Between 1990 and 2011, temporarily reducing grazing on Australian farms yielded economic benefits in 20-40 % of years, especially during periods of low crop yields, by optimising forage utilisation and increasing profitability under variable conditions (67).

Incorporating compost or manure

The application of compost or manure improves soil quality by enhancing structure, fertility and water retention, which are crucial for optimal crop production. Balancing the carbon-to-nitrogen ratio is vital; ratios above 25 to 30:1 may cause nitrogen deficiency in maize crops. Organic farming practices, such as composting and crop rotation, promote sustainable production and significantly reduce erosion rates compared to conventional methods (68). Soil carbon content increased by 5.5 % to 35.3v in maize plots that received compost amendments compared to control plots that only received synthetic fertilizers in Laos, Thailand and Vietnam (69).

Animal manure and other amendments derived from animals, such as chicken litter (comprising chicken faeces, feathers, bedding materials, feed and water), are primarily appreciated for their role in improving soil fertility through the provision of essential macro and micronutrients (70). Systems receiving manure applications, as opposed to plant–based amendments, not only saw greater increases in yield but also had the potential to eliminate most or all nitrogen fertilizers without experiencing yield reductions (43). This suggests that nitrogen provision plays a pivotal role in the yield advantages associated with organic amendments. Furthermore, animal manure can enhance long-term soil fertility by promoting short -term microbial immobilisation of nutrients, thereby mitigating losses through leaching, nitrification and denitrification (71).

Sustaining soil health as a way to nurture regenerative agriculture

Enhancing soil health has garnered significant attention, with many articles addressing the enhancement of soil quality through various synonymous objectives, such as 'improving soil quality' and contributing to soil fertility (26), enhancing soil health and 'improving soil quality' in Fig. 2 (72).

Regenerative agriculture is a collection of techniques that harness favourable soil-plant interactions that occur naturally, minimizing the need for external inputs and making use of ecological approaches to farming. The cornerstone of regenerative agriculture is soil, but it also interacts with the crop canopy and site-specific crop management (22, 73). The primary goals of implementing regenerative agriculture are to preserve soil fertility by optimising nutrient concentrations and to enhance crop protection measures in agricultural fields by increasing the soil's resistance to disease. Soil–related metrics, such as Soil organic carbon, bulk density and pH, are pivotal for evaluating regenerative agriculture, particularly in the context of Australian mixed farming, where restoring soil health is imperative, given the unique characteristics of the soil (74).

Traditionally, indigenous agricultural methods, such as three-sister cropping, combined corn, squash and beans in the same field, promoting productivity and soil health through symbiotic relationships and sustainable practices. Incorporating legume cover crops into the soil boosts soil biological activity and augments nitrogen availability, supporting the growth of multiple crops and enhancing overall soil health and productivity (75). Conventional farm management predominantly emphasises nitrogen (N), phosphorus (P) and potassium (K) levels, neglecting holistic soil health indicators that are crucial for long–term fertility and sustainability (41).

Soils represent the Earth's second–largest carbon sink, harbouring twice as much carbon as the atmosphere and vegetation combined owing to their ability to sequester carbon. The sequestration capacity varies depending on factors such as soil type, environmental conditions, soil mineralogy and land management practices. Carbon sequestration in agricultural soils not only aids in reducing atmospheric carbon dioxide levels but also enhances soil health, thereby fostering more productive landscapes (76). Earthworms and consequently, the density of macropores, can significantly influence soil drainage. Their populations greatly increase under conservation tillage, thereby enhancing drainage. Recognition of the importance of soil health in agriculture has prompted land stewards to move beyond conventional land management practices toward the adoption of sustainable, soil-focused approaches. In general, elevated species diversity is known to play a stabilizing role in ecosystem function (77).

Impact of management practices on microbial load

Soil health differs from fertility in that it encompasses natural cycles, diverse biodiversity and the capacity to provide ecosystem services beyond nutrient levels, thereby emphasising the holistic well-being and resilience of soil ecosystems for sustainable agriculture. The implementation of cover cropping enhances soil microbial abundance, resulting in

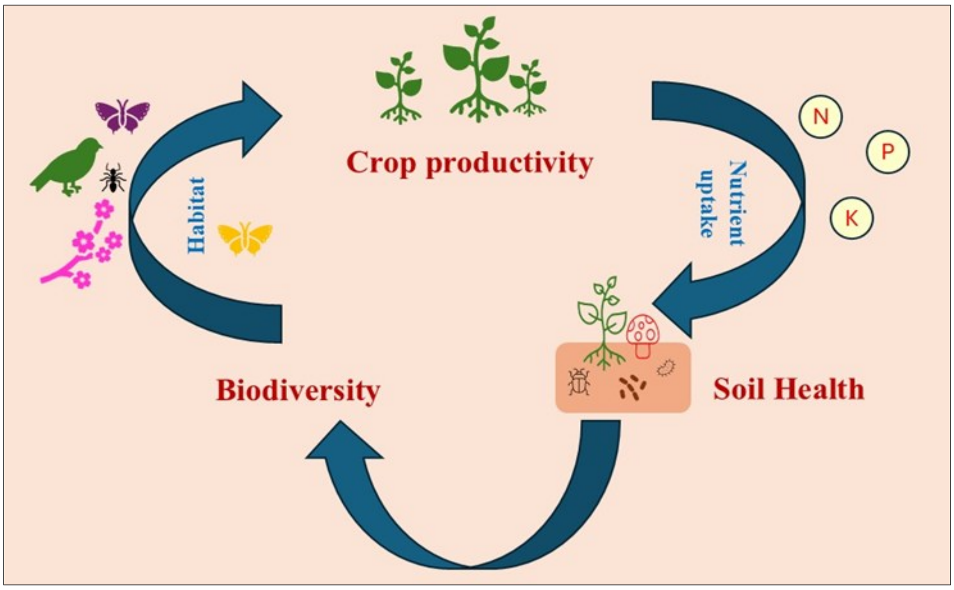

Fig. 2. Dynamic interplay supporting sustainable crop systems.

improvements in soil fertility, nutrient levels and organic content by 15-41 % (78). Regenerative agricultural practices enhance both the diversity and abundance of beneficial microbes, including mycorrhizal fungi and nitrogen-fixing bacteria, thereby promoting healthier soil under natural farming systems compared to conventional agriculture (79).

Tree root-associated microbial communities in apple orchards vary significantly depending on the type of floor management system used, which affects the diversity of soil microbiota under regenerative agriculture practices. Regenerative agricultural practices affect plant-associated microbial communities and influence plant growth. Understanding and modulating these communities can reduce chemical inputs and enhance crop health (80).

The interaction between plant roots and soil microorganisms has a significant impact on nutrient availability and uptake. Root exudates are crucial for making phosphorus (P) available to plants and enhancing microbial activity. Various microbial processes break down and mineralize organic forms of nitrogen (N), phosphorus (P) and sulphur (S), releasing their inorganic forms into the soil. The flavonoid pathway, facilitated by root exudates, plays a crucial role in legume rhizobia-mediated nitrogen fixation (81).

Mycorrhizal fungi may further enhance soil water and nutrient efficiency by creating stable aggregates and facilitating the release of phosphate and micronutrients. (82). While microbial bioeffectors show promise in boosting crop productivity and nutrient conservation, evidence mainly arises from controlled greenhouse experiments, with a limited demonstration of tangible benefits in field environments, necessitating further research for practical applications. The challenges in excluding environmental stressors and native microbial communities, which might hinder the establishment of plant-microbial interactions, contribute to inconsistent results (83).

Management practices in regenerative agriculture can reduce pathogen load by altering rhizosphere bacterial communities, improving soil health and suppressing *Candidatus Liberibacter asiaticus,* as shown in the study (84). The effects of tillage and straw return on the soil microbiome diversity were studied. Short–term practices, such as rotary tillage and maize straw return, increase bacterial diversity, with potential biomarkers identified for regenerative agriculture. Management practices in olive cultivation affect soil microbial communities. Sustainable techniques such as organic conditioners and vegetation cover influence the microbial load and enhance soil quality and crop development (85).

Carbon sequestration and organic matter accumulation

Plants are the primary source of organic matter in soils; the amount of organic matter that plants provide varies substantially in place and time and depends on the type of ecosystem. Plants continuously emit exudates from their roots, root tissue turnover occurs and aboveground plant waste is deposited. Additionally, plants provide organic carbon to their mycorrhizal symbionts, which are among the major sources of organic carbon in soil. Inputs follow diverse paths in the soil, depending on their water solubility, the energetic return on investment in microbial decomposition and the soil environment. Enhanced crop rotation is frequently associated with cover cropping strategies, as cover crops can be used to decrease fallow or boost plant diversity. According to research, increasing the complexity of crop rotation increases soil organic carbon (SOC) at a mean rate of 0.2 Mg C per ha per year (86). It was found that incorporating cover crops into rotations sequestered 0.56 Mg C per ha per year, with multispecies and leguminous cover crops boosting soil organic carbon more than monoculture and grass species (47). The use of organic amendments has been shown to result in SOC accumulation rate of 0.5 total carbon per hectare per year (87).

Regenerative agricultural practices, such as cover cropping, can sequester atmospheric carbon into soil organic matter, benefiting agriculture and mitigating climate change by fixing carbon from the atmosphere. The plant microbiome contributes to carbon sequestration in regenerative agriculture by utilising plant-derived carbon through rhizodeposition, thereby enhancing soil carbon storage and promoting sustainable practices that mitigate CO_2 emissions. Increasing soil carbon sequestration is one way to reduce emissions from agricultural activities, as soil serves as a significant global carbon sink. Although estimates of historical SOC loss vary widely, they typically range from 55 to 78 Pg in the 1550 Pg total SOC pool (88).

Impact of regenerative agriculture on water retention capacity

Regenerative agriculture promotes functional biodiversity, improves soil moisture retention and facilitates sustainable water management. Regenerative agricultural practices prioritize natural ecosystem resilience, promoting long–term agricultural viability and ecosystem health through improvements in soil health and water availability. Regenerative agriculture integrates efficient irrigation methods including drip irrigation and sprinkler systems. These approaches ensure precise water distribution to the plant roots and minimize losses due to evaporation and runoff. By delivering the right amount of water at optimal times, they enhance water-use efficiency and reduce waste (89).

Soils managed under regenerative practices retain more water, foster crop resilience with reduced irrigation needs and improve hydrology by curbing runoff and erosion, ultimately promoting sustainable water use and healthier soil ecosystems through enhanced fertility and structure. Five primary objectives or promises define regenerative agriculture and water use. The primary objective is to maintain optimal crop evapotranspiration over time for rainfed crops, ensuring sufficient yields alongside other essential inputs, such as nutrients and effective soil management. The second objective involves reducing surface runoff and flooding while promoting better water quality and potential decreases in soil salinity. The third objective is to effectively manage rainfall and irrigation water at both field and farm scales. The fourth objective focuses on improving the management of catchment water withdrawals and allocations through coordinated management of soil, rainfall and freshwater resources. Additionally, the fifth indirect objective involves increasing soil organic matter content and carbon sequestration (90). Practices such as zero–tillage agriculture and mulching, aimed at enhancing carbon and organic properties, offer benefits such as improved root development and moisture retention through increased carbon levels and biological activity (91).

Crop productivity under regenerative agriculture

In regenerative agriculture, surface crop residues and undisturbed soil aggregates play key roles in retaining soil moisture. However, the resulting yield improvements are usually limited to arid regionsA with scarce water resources, emphasizing that their impact on crop productivity depends on specific environmental conditions (37, 92). Factors such as soil greenhouse gas emissions, particularly N_2O, are crucial considerations in assessing the climate change mitigation potential of regenerative agriculture practices, including reduced tillage and cover cropping, underscoring the necessity for comprehensive environmental impact evaluations in Fig. 2 (93).

Regenerative agriculture may have 29 % lower grain production but 78 % higher profits than conventional methods, demonstrating profitability without significantly sacrificing crop productivity. Regenerative agriculture, particularly Organic and Conservation Agriculture (OCA), enhances crop productivity by up to 59.7 million metric tons in China (94). Regenerative agricultural technologies, such as intercropping, mulching and crop rotations, positively impact cowpea productivity in drylands, enhancing soil fertility and agricultural output.

Impact of regenerative agriculture on the environment

Regenerative agriculture not only focuses on system regeneration and ecosystem enhancement but also aims to minimize environmental impacts. One of its key objectives is to reduce environmental harm and pollution. This approach is widely supported by both scientific researchers and farming communities, who agree on the importance of enhancing ecosystem health alongside sustainable production. A thriving agroecosystem is characterised as a resilient system capable of providing ecosystem services, including provisioning, regulating, habitat and supporting services, as outlined by researchers in Fig. 2 (13).

The imperative for enhanced agricultural sustainability, significant greenhouse gas emissions and climate shifts underscores the need for adaptive strategies to ensure food security amidst predicted severe weather events. Regenerative agriculture, tailored to local contexts, offers cost-effective solutions for small-scale farming, fostering resilience and addressing food supply challenges by emphasising localised production systems and economies, regardless of the diverse impacts of environmental, climate and financial resources on agricultural infrastructure in developing countries (95).

The environmental benefits of carbon sequestration are significant, encompassing the reduction of greenhouse gas emissions, mitigation of global warming and contributions to climate stabilization (96). Regenerative agriculture helps adjust and enhance the resilience of agricultural and food security systems to climate change across various levels while also mitigating greenhouse gas (GHG) emissions from farming activities (97).

In contrast to conventional tillage approaches, no-tillage methods have shown potential to reduce global warming potential by enhancing soil aggregation and porosity (29). The adoption of no-tillage techniques can reduce the global warming potential by up to 19 % compared to conventional tillage. However, variability in factors such as soil type and crop choice can sometimes lead to an increase of up to 20 % due to emissions from residual organic matter and fluctuations in soil carbon and nitrogen levels. On average, this variability has resulted in a net reduction in global warming potential of 7.6 % (98).

Multispecies rotational grazing systems demonstrate a % lower emission footprint per unit area of land compared to conventional grazing practices. Addressing the negative environmental impacts of livestock, including greenhouse gas emissions, increased flood risks and compromised water and air quality, is a crucial component of regenerative agriculture (99). A recent study conducted in China examined various cropping systems to determine their potential for soil carbon sequestration and their findings indicated that across different crop rotations and management approaches, soil carbon sequestration offsets an average of 10 % of total greenhouse gas emissions (including N_2O, CH_4 and CO_2), with a maximum offset of 30 % (100).

Conclusion and way forward

Regenerative agriculture garners interest from a broad range of participants, spanning small-scale farmers aligned with the alternative farming movement to large corporations operating in markets worldwide. Regenerative agriculture surpasses conventional methods and should be adopted by farmers, requiring fewer resources, such as fertilisers, water for irrigation, labour and pesticides. This reduction in input costs enhances crop productivity and uplifts the livelihoods of farmers. This holds significant potential for addressing the multifaceted challenges of mitigating climate variability, restoring soil health, conserving water resources and combating emerging pest resistance in modern farming practices. By emphasising principles that prioritise soil health, biodiversity and ecosystem resilience, regenerative agriculture offers a pathway toward sustainable food production and environmental stewardship. Through the implementation of diverse practices such as cover cropping, crop rotation, agroforestry and holistic grazing, regenerative agriculture not only enhances soil fertility and water retention but also mitigates greenhouse gas emissions and fosters a healthier relationship between agriculture and the surrounding environment. Moreover, regenerative approaches can contribute to the resilience of farming systems in the face of climate change, economic uncertainty and evolving societal needs. Adopting regenerative agriculture necessitates collaborative efforts from farmers, policymakers, researchers and consumers. By supporting and scaling up regenerative practices, we can cultivate landscapes that are not only productive and profitable but also regenerative and sustainable for future generations. Regenerative agriculture faces several challenges, including the need for extensive farmer education and initial financial investment. Limited policy support and market infrastructure for regenerative products have hindered their widespread adoption. Climate change introduces complexity through unpredictable weather patterns and extreme weather events. Additionally, robust metrics and long–term data collection are required to measure and verify environmental benefits. Addressing these issues is crucial to the success of regenerative agriculture.

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Authors' contributions

KV conceptualized and wrote the original draft. RM conceptualized, supervised and reviewed writing and editing. KR, SS, BK, SC and AM contributed to the review the manuscript.

Compliance with ethical standards

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