Discover Sustainability

Review

Importance of regenerative agriculture: climate, soil health, biodiversity and its socioecological impact

Alam Sher[1] · Hongxing Li[1] · Aman ullah[2] · Yasir Hamid[3] · Bukhtawer Nasir[4] · Jiwang Zhang[1]

Received: 20 June 2024 / Accepted: 12 November 2024
Published online: 04 December 2024

Abstract
Agriculture is facing a severe threat to its sustainability due to the growing demands for food, feed, and other renewable nonfood raw materials in the face of global warming. Regenerative agriculture is increasingly recognized as a vital solution to a range of ecological and social issues. It actively revitalizes ecosystems, focusing on soil health, biodiversity, and mitigating climate change, going beyond sustainable practices. Governments and other organizations at all levels, from global to regional, are exploring how regenerative agriculture can be integrated into climate change initiatives to sustain ecosystem. This powerful benefit can be achieved without reducing yields or farmer profits. Soil, as a living and dynamic environment, is home to a diverse range of micro- and macro biota that contribute to its characteristics. Healthy soil is characterized by favorable physical properties (texture, water-holding capacity), chemical properties (pH, soil organic matter; SOM), and biological properties (microbial diversity, and soil respiration), which are essential for nurturing nutritious and profitable crops and improve human health. Regenerative farming is attracting interest from the public, private, and nonprofit sectors to improve soil health and sustain ecology. Several academics and non-governmental organizations have attempted to explain the scope and significance of regenerative agriculture. This review outlines how regenerative agriculture practices can mitigate global warming, improve soil health, boost biodiversity, and its socioecological impacts. For future prospects, further scientific research required to examine the effects of regenerative agriculture on both livestock and human health, in order to promote a healthier community.

Keywords Regenerative agriculture · Soil health · Global warming · Mitigation · Biodiversity · Socioeconomics

1 Introduction

The world's population and agricultural output have been two concurrent phenomena that have received a lot of attention over the last few decades because they have the potential to pose risks to social, economic, and environmental sustainability. The population of the world is expected to increase by an estimated 83 million people per year and reach an estimated 9.7 billion in 2050, with emerging nations accounting for a large portion of this growth [1]. A major breakthrough in agricultural farming is linked to this intensive industrial food production which is also known as intensive or factory farming. Intensive farming is farming system which increases farm output while also improve land efficiency by

✉ Alam Sher, alamsher@sdau.edu.cn; ✉ Jiwang Zhang, jwzhang@sdau.edu.cn | [1]College of Agriculture, Shandong Agricultural University, Taian 271018, Shandong, China. [2]Department of Zoology, Ghazi University, Dera Ghazi Khan, Pakistan. [3]Ministry of Education (MOE) Key Lab of Environ Remediation and Ecology Health, College of Environmental and Resources Science, Zhejiang University, Hangzhou 310058, China. [4]Department of biotechnology, University of Faisalabad, Faisalabad, Pakistan.

sowing different crops and modified grazing. These agricultural practices have produced food that has led to tremendous development, which is known as the "Green Revolution" [2].

The idea of replenishing what has been used up and fixing what has been harmed is known as regeneration. It often deals with land that has deteriorated after years of intense, monoculture farming. One method to completely transform the land is through regenerative agriculture, which also replenishes essential nutrients and restores biodiversity. Regenerative agriculture, also known as outcome-based agriculture, is a method of producing food that maintains biodiversity, the climate, water resources, and soil health while also increasing farm productivity and profitability. It consists of a variety of methods supported by cutting-edge technology that can effectively address the problems posed by climate change through the restoration of soil health and the preservation of the land's ecology to improve ecosystem. Compared to conventional agriculture, regenerative agriculture uses less water and other inputs while halting deforestation and land degradation. In addition to increasing agricultural productivity and profitability, it preserves and enhances soil, biodiversity, climate resilience, and water resources as well as social justice and rural livelihoods [3].

1.1 Regenerative Agriculture what is it?

Sustainability refers to the ability to maintain something at a specific pace or level. In the context of our current reality, where over 38% of the world's agricultural land has already been impacted by degradation, sustainability alone is no longer sufficient. We must now focus on regeneration. At re-nature, we believe that "regeneration is the destination—sustainability is a bridge," when it comes to land and farming. Regenerative agriculture is a type of sustainable agriculture that utilizes soil-based methods instead of seed-based ones. It adapts to the specific agroecosystem in which it is practiced. Supporters and practitioners of regenerative agriculture argue that these techniques can reduce greenhouse gas emissions, improve financial returns for farmers, prevent soil erosion and depletion, actively build soil, provide crop nutrients with minimal external inputs, yield healthy and abundant crops with minimal weeds and pests, and promote human health [4]. Increasing soil organic matter enhances the soil's ability to store carbon and facilitates nutrient cycling. Regenerative agriculture is characterized by a set of principles and practices designed to restore and enhance the health of agricultural ecosystems. Key practices include no-till farming, cover cropping, crop rotation, and the integration of livestock. These methods aim to improve soil health, increase biodiversity, and enhance ecosystem services [5–7]. RA is often viewed as a movement rather than a specific set of practices, emphasizing the regeneration of agricultural resources such as soil, water, and biota. This movement aligns with global efforts to improve ecosystem function and sustainability [6]. Despite the lack of a standardized definition, RA is generally understood as a framework aimed at improving soil health, biodiversity, climate resilience, and ecosystem function [4, 7]. Research indicates that RA can provide significant economic and environmental benefits. For instance, regenerative farming systems have been shown to offer greater ecosystem services and profitability compared to conventional farming methods. Insecticide-free regenerative farms, for example, have demonstrated lower pest abundance and higher profits, despite lower grain production [5]. This suggests that RA can be more profitable and environmentally sustainable than conventional farming systems. Moreover, RA practices such as no-till farming and cover cropping can sequester soil organic carbon, contributing to climate change mitigation. These practices also enhance soil health, leading to more resilient agricultural systems capable of producing nutritious food while reducing environmental impacts [8]. Regenerative agriculture also has the potential to enhance social and human capital. It promotes a paradigm shift in farming, encouraging farmers to adopt practices that are not only environmentally sustainable but also socially beneficial. This shift is crucial for addressing climate change and environmental degradation more effectively [9]. Additionally, RA emphasizes the importance of local knowledge and context, integrating scientific and traditional knowledge to create more resilient and sustainable farming systems [7]. Aimed at rebuilding natural capital in parallel with social and human capital and done in ways that also create physical and financial capital. The impact of RA on crop yields varies between regions. In tropical areas, the application of biochar and other RA practices can lead to substantial yield increases due to the low fertility and acidic nature of the soils [10]. Conversely, in temperate regions, where soils are generally more fertile and receive higher fertilizer inputs, the yield benefits of RA practices like biochar application are less significant [10]. However, even in temperate regions, RA can lead to higher profitability despite lower yields, as seen in regenerative corn production systems in the Northern Plains of the United States [5]. In today's world, the focus must be on regeneration rather than simply maintaining the current state of our land. We need to employ regenerative approaches to heal our affected agricultural land. Regenerative agriculture is often portrayed as a "new" or "revolutionary" form of farming in popular discourse, but this is not entirely accurate. The term "indigenous" is used to describe tribes or peoples who have a long history of settlement and connections to a specific area, often referring to populations that existed before the colonial or "pre-Age of Discovery/Exploration" periods in many parts of the world [11]. The objectives of regenerative agriculture are to produce enough nutrient-dense food to feed the global population, reduce greenhouse gas emissions and mitigate climate change by storing carbon in the soil, restore biodiversity and improve natural habitats, prevent further deforestation and conversion of grasslands by increasing productivity on existing farmland, and improve farmer livelihoods and ecosystem. Figure 1 illustrates the importance of regenerative agriculture.

1.2 History of regenerative agriculture

The history and origins of regenerative agriculture, the terms "regenerating agriculture" and "regenerative farming" gained popularity in the early 1980s after being accepted by the Rodale Institute in the United States. For many years, the Rodale Institute has led the natural agriculture movement through research and publishing, particularly the periodical Organic Horticulture and Farms. Regenerative agriculture as "one that, as productivity rises, expands our land and soil biological production base [12]." It is inherently very stable both biologically and economically. It has little to no effect on the ecosystem outside of the boundaries of the agricultural property or field. It produces food that is free of biocides [13]. By utilizing ecological farming techniques and minimizing reliance on outside inputs, regenerative agriculture is a collection of methods that highlights and maximizes positive soil–plant interactions that occur naturally [14]. Since the late 1970s, the term "regenerative" has been linked to agriculture and farming [15]. However, the words "regenerating agriculture" and "regenerative farm" gained popularity in the early 1980s after being adopted by the US-based Rodale Institute. The Rodale Institute has been at the vanguard of the organic agriculture movement for many years through its publications and research, which includes the periodical Organic Horticulture and Farms. Regenerative farming is defined as "one that, at higher levels of efficiency, improves our soil's and land's biological resource base," according to Robert Rodale [12]. In agricultural regeneration, Robert Rodale outlines seven trends [16]. A system transitions to being regenerative through these seven characteristics. A regenerative system is characterized by seven tendencies (Ps): 1. Pluralism, which refers to the diversity of plant species. 2. Protection, which emphasizes the use of cover crops to reduce soil erosion and boost soil surface microbial populations.3. Purity, which involves the intentional absence of fertilizers and pesticides in production. 4. Permanence, which recommends an increase in perennials and plants with strong roots. 5. Peace, which means living in harmony with nature and developing with it rather than opposing it. 6. Potential, which refers to the easily accessible nutrients that rise to the soil's surface and are used by plants. 7. Progress, which includes the constant improvement of soil quality in terms of composition and water-holding capacity.

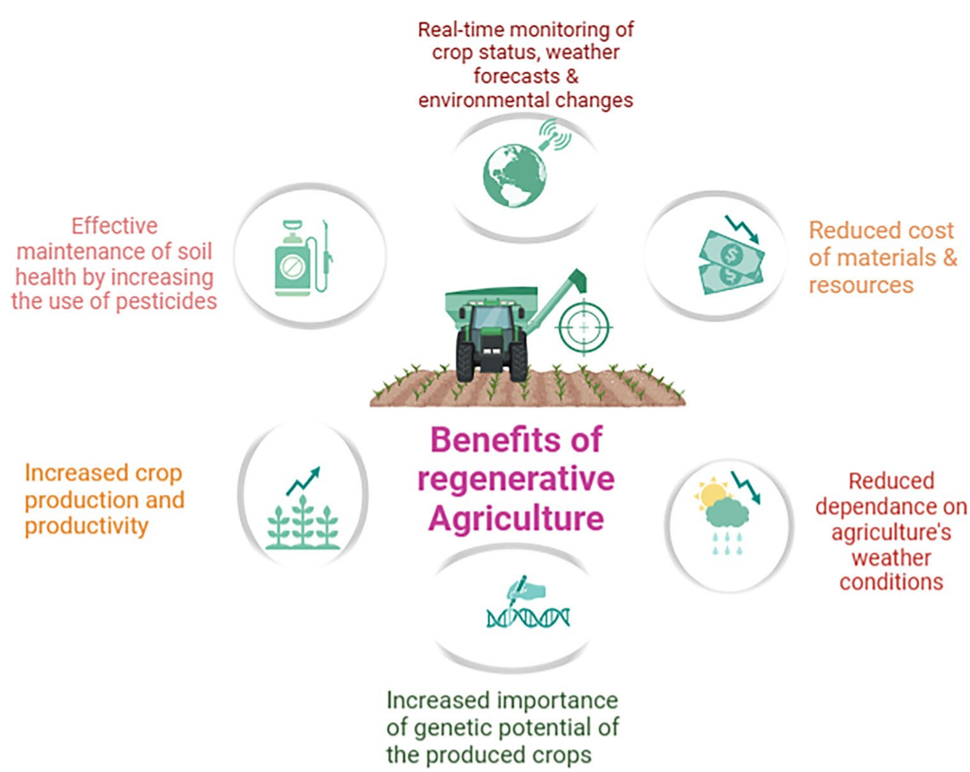

Fig. 1 benefits of regenerative agriculture

Understanding these seven inclinations is beneficial for formulating the essential components required to transition to a regenerative farming system. Christian Shearer's "Regenerative Agriculture Lineages" are Farmers themselves have developed a viable farming system that supports ecosystem services through ecologically oriented production, involving various activities. Regenerative agriculture fundamentally challenge the current food production model, which prioritizes gross revenues at the expense of net gains for the farmer. One of the main components of this productive farming method is that regenerative farmers have been able to successfully control pest populations and use less expensive inputs like fertilizer and pesticides due to their value for soil biology, organic matter, and biodiversity on their fields. Soil organic matter is a more significant determinant of proximal farm profitability than yields, as regenerative farms have diverse income streams from a single field or multiple marketing strategies for their products.

1.3 Principles and practices of regenerative agriculture

Efforts to promote regenerative agriculture, such as comprehensive feeding, cover cropping, and limited soil disruption, have received varying support. The term holistic feeding has faced criticism, with some arguing that it does not accurately represent the practices taught by Savory or implemented on their own farms. Recent studies have shown the benefits of cover crops for soil carbon, soil microbiota, physical qualities, and weed control. Overall, there is increasing acceptance of minimal soil disturbance due to its connection to sustainable agriculture. However, there is also criticism of regenerative practices, particularly regarding how they are promoted in mainstream media without proper context or consideration of accepted science. This criticism acknowledges that these actions can be beneficial in farming, but questions the way they are framed and marketed.

Farmers engaged in regenerative agriculture adhere to five fundamental concepts and principles:

1. They avoid the use of chemicals, machines, and physical methods in field treatments, aligning with the principles of prehistoric regenerative agriculture.
2. They use cover crops year-round to prevent bare soils and reduce erosion. This practice also provides pasture and grazing materials for livestock and poultry.
3. They increase biodiversity through practices like silvopasture, diversified agriculture, and crop rotation.
4. They utilize livestock to support farming productivity.
5. They preserve the live roots of perennial crops.

These concepts aim to sustain a cycle of regeneration in agriculture year after year and season after season. However, they are not comprehensive and their implementation varies based on the specific characteristics of each farm. Regenerative agriculture involves more than just replenishing and restoring trees, incorporating organic matter, and improving soil fertility. It also has environmental benefits such as reducing soil and water pollution from chemical inputs, enhancing biodiversity, and storing carbon to mitigate climate change. Planting more forests and sequestering carbon in the soil can improve air quality and mitigate the effects of greenhouse gases.

Furthermore, protecting ecological systems is crucial for preserving biodiversity. Regenerative agricultural practices include grassland and zero-till cutting, which reduce soil erosion and carbon emissions. Specialized equipment, such as disc planters or drills, are used for seeding in these practices. Pasture cropping, which involves using grains as grazing grass, is another important aspect of sustainable agriculture that helps prevent erosion. It showcases planting without tilling, as soybean seeds sprout from the remnants of a previous grain harvest. Organic annual cropping, which involves trimming organically, using non-chemical insecticides and fertilizers, is recommended to minimize negative impacts on the environment and human health. Finally, regenerative agriculture practices can benefit agro-ecological related businesses by promoting a healthier population and environment [17, 18]. Figure 2 explains regenerative agriculture practices. There are only a few studies about regenerative agriculture (RA) effect on soil health but a lack of studies about RA effect on biodiversity, climate change, and socioeconomic policies for the betterment of farmer livelihood and human health. In this review, we briefly explained RA principles and practices and how these practices mitigate global warming, improve soil health, and ecology. We also explained the adoption constraints, policies, and socioecological benefits of these RA practices on rural community. There are also future prospects for scientists and policymakers on how RA practices improve both livestock and human health and increase their lifespan.

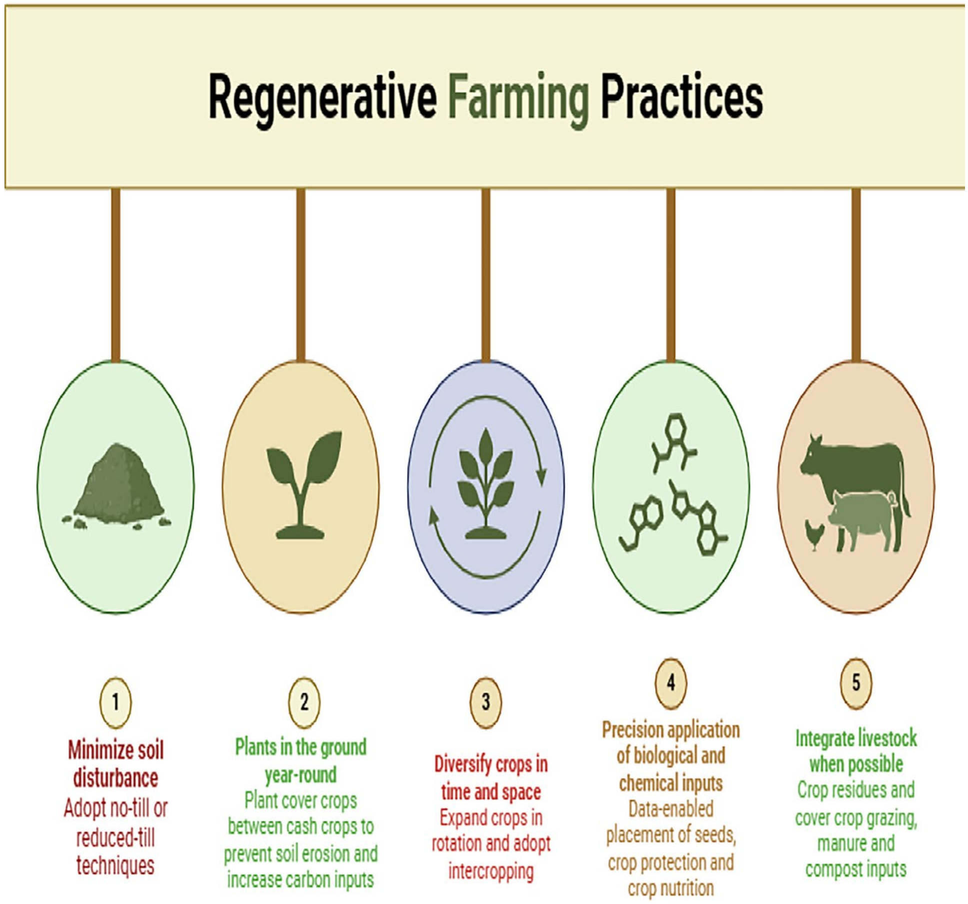

Fig. 2 Regenerative Farming practices

2 How could regenerative agriculture help to reduce the impact of climate change?

With the prediction of a significant increase in plastic production over the next 20 years, petrochemical feedstocks, accounting for 14% of oil consumption in the manufacturing sector, will be responsible for half of the projected rise in oil demand from now until 2050 [19, 20]. In order to address the root causes of plastic pollution and the climate emergency, it is crucial to find substitutes for materials derived from petroleum. The unsustainable growth of these products currently results in the production of over 400 million tons of resins, fibers, and polymers derived from fossil fuels annually, a number expected to more than double by 2050. Unfortunately, most of this manufacturing ends up in landfills, leading to a high rate of leakage into the environment, posing a threat to ecosystems and human well-being [21].

It is widely recognized that human activities, specifically the emissions of greenhouse gases, are the primary cause of climate change. These emissions contribute to long-term, harmful changes in the climate that are extremely difficult, if not impossible, to reverse. Consequently, there has been a global effort to reduce greenhouse gas emissions over the past few decades. However, these initiatives have not been very successful. In 2020, due to restrictions and disruptions caused by the COVID-19 pandemic, there was a temporary 5.4% decrease in global greenhouse gas emissions. Unfortunately, by 2021, emissions had already rebounded to levels nearly identical to those before the outbreak [22]. The year 2020 saw a decrease of 1.9 Gt CO_2/yr, resulting in a total of 34.8 Gt CO_2/yr, which is comparable to the emissions level in 2012. However, in 2021, emissions reached approximately 36.4 Gt CO_2/yr, slightly lower than the 36.7 Gt CO_2/yr recorded in 2019. The main reason for this increase is the rise in energy consumption, particularly from gas and coal, surpassing 2019 levels due to power generation, while greenhouse gas emissions from oil have remained below 2019 levels due to reduced demand for global transportation [23].

Sequestering carbon from agriculture has the potential to significantly reduce the effects of climate change. This significant gain can be achieved with biologically-based regeneration techniques without affecting farmer earnings or yields. Numerous studies confirm that regardless of the type of soil and temperature, they have an impact on sequestration capacity. It is estimated that there are 3.5 billion tillable acres on Earth that could be used for viable organic farming, which has the potential to sequester about 40% of the world's current greenhouse gas emissions [24]. The Rodale Center advocates for a swift, countrywide switch from the current petroleum-based agricultural methods to more sophisticated "post-modern" systems that incorporate best practices derived from repeated research. This approach, known as regenerative organic farming, emphasizes replenishing assets through natural processes that nourish and enhance the soil while eliminating hazardous chemical inputs [24]. Globally, the agribusiness industry is facing significant challenges as governments, corporations, agronomists, farmers, and end users strive to achieve a delicate balance between the needs of people (or the "right to food"), productivity, financial gain, and ecological sustainability. However, due to the wide diversity of agroecosystems, farm systems, and regulatory frameworks, the nature of these challenges can vary significantly across different times and locations. This reality challenges the idea that there is a single, globally applicable issue description or specific agronomic remedy that is RA practices which can effectively alleviate pressures on the world food supply. Table 1. Describes the effects of regenerative principles and practices on soil health, ecology, and climate change mitigation.

3 Regenerative agriculture practices for improving soil health

Soil is a significant field of study in biology and ecology. As our knowledge and technology continue to advance, it is crucial to consider the direction of agricultural study and application. Researchers argue that a substantial portion of future initiatives should focus on enhancing and maintaining the ability of our agricultural system to regenerate itself, particularly in terms of soil quality [25]. This includes ecological and land-use borders that support biodiversity, human wellness, and the quality of air and water. In a more modern definition, the International Technical Panel on Terrains (ITPS) describes soil health as "the capacity of the soil to sustain the efficiency, diversity, and ecological services of terrestrial ecosystems." So, what exactly makes soil healthy? Healthy soil has the ability to function as a living environment that supports plants, animals, and mankind [26], thereby improving human health and overall ecosystem [18]. Soil health refers to the capability of soil to maintain its vital living system characteristics, including the physiological (appearance, water-holding ability), biological (pH, soil organic matter; SOM), and natural (microbial diversity, N mineralization, and soil respiration) parameters necessary for the growth of flourishing, profitable crops. Soil is believed to be a living, dynamic ecosystem that houses a diverse range of microorganisms and macro biota that contribute to its characteristics. However, contemporary technology-driven agricultural intensification has reduced soil's ability to sustain its functions, leading to long-term negative implications for manufacturing and the loss of environmental services. The primary goal of Regenerative Agriculture (RA) is to improve soil health by increasing organic matter levels and enhancing soil fertility and production. Regenerative agriculture (RA) practices are extremely reliable, both biologically and economicall. They have minimal to no negative effects on the surrounding ecosystem beyond the farm or field. RA generates food that is free from biocides. As we strive to reduce our dependency on non-renewable resources, RA allows for the active participation of an increasing number of individuals [28]. Soil serves as the foundation of regenerative agriculture [8]. In addition to crop canopy and site-specific crop management, regenerative agriculture emphasizes soil health [29]. The main goals of implementing regenerative agriculture are to preserve soil fertility by optimizing nutrient concentrations and enhance crop protection methods in agricultural areas by increasing the soil's ability to resist disease [8]. Indigenous agricultural techniques in the United States have always aimed to increase yield while preserving soil health. For example, the Navajo, Cahokian, Mvskoke, and Mississipian tribes practiced a technique called three sister cropping, which involved cultivating maize (Zea mays L.), squash (Cucurbita spp.), and beans (Phaseolus vulgaris L.) on one field [30]. The climbing beans, through symbiotic and companion plant interactions, fix nitrogen in the soil for all three plants. Maize, being the primary staple of most cultures, assists the beans by providing necessary nutrients. Squash acts as a mulch and cover crop, suppressing weeds and pests, preventing soil erosion, and retaining soil moisture, benefiting all three plants. Conversely, legumes grown in the same area fix nitrogen in the soil, creating a favorable environment for all three crops to thrive. Regenerative agriculture practices such as no-till farming, cover cropping, and agroforestry in tropical and subtropical regions where soils has less nutrient and degraded increased soil health and soil organic carbon (SOC) levels. For example in tropical soils the use of biochar enhanced crop yields upto 25%, by liming and fertilization effects, as compared to temperate soils [8]. Raising of forests and rearing of livestock and in tropical regions increased soil carbon and provided multiple co-benefits [27]. Livestock plays a crucial role in the holistic approach to sustainability in regenerative agriculture. The grazing habits of sheep and cattle strongly impact improved grass productivity and

Table 1 Regenerative Agriculture impact on Soil health, Ecology and mitigation strategies

Principles	Practices	Restoration of soil health	Improved ecology	Mitigation strategies	References
Soil covering	Intercropping	More organic carbon that improve soil health	Increased microbial biomass		[91]
	Intercropping	Reducing soil disease			[92]
	Intercropping	Improved soil health			[93]
	Intercropping	Improved soil ecosystem			[94]
	Intercropping		Increased functionalities of soil microorganisms		[95]
	Intercropping	Improved soil health and eco-system	INCREASE diversity of micro-habitat		[96]
	Crop diversification	Increased soil health			[97]
	Crop diversification	Increased soil health	Enhance soil microbial com-munities		[96]
	Crop rotations	Soil health Improved			[56]
	Crop rotations	Soil health Improved	High microbial biomass		[98]
	Crop rotations	Soil health Improved	Increased functional comple-mentarity		[96]
	Ground cover	Soil health Improved	Improved biodiversity		[99–102]
	Mulch, cover crops, permacul-ture	Soil health Improved			[103, 104, 105]
Plant diversity	Agroforestry	Soil health Improved	Improve biodiversity		[103, 104, 105]
Avoid pesticides	Agroforestry	Soil health Improved	Improve biodiversity		[103, 104, 105]
	Use farm inputs like animal manure instead ofc synthetic pesticides or fertilizers	Improve soil health by increas-ing SOM		Increased carbon storage of arable lands by creating Humic substances	[24]
Animal grazing	Silvopastoral livestock systems	Improve soil health			[106]
	grasslands		Increased levels of biodiversity		[106]
	Rotational grazing			Increased 3.6% top soil carbon storage	[31]
Decreased GHG emssions	Reduce use of inorganic fertiliz-ers or pesticides			reduced N2O and CO2	[107, 108]
	Enhance forage productivity and increased forage availability			reduced N2O, CO2, CH4	[109, 110]
Enhanced natural carbon sinks	pasture cropping			Changing cropping pattern to pasture cropping, or chang-ing cropping scheme like mixing pastures to cereals can enhance by perennialization SCS	[111, 112]
	planned grazing	Improve soil health	Increase competitiveness of perennial species,	improve SCS ability	[113–116, 117]

Table 1 (continued)

Principles	Practices	Restoration of soil health	Improved ecology	Mitigation strategies	References
	add soil amendments			improve SCS ability by reducing nutrients deficiencies	[118, 119]
GM	Reduced tillage with green manure	Enhanced soil physical metrices, by improving soil aggregate stability			[39]
OA	Reduced tillage with organic amendments	OA increased soil chemical and biological metrices, like SOC, POC, PON, total N, K, P, available P and exchangeable cations			[39]
(GM&OA and NT&OA)	Reduced tillage with organic amendments	Increased overall soil quality			[39]

enhanced carbon sequestration in rangelands. For instance, sheep grazing on regenerative rotational soil can increase organic carbon content in the topsoil by 3.6% and boost springtime grass production by 30% [31]. Consequently, defining regenerative farming presents a challenge. Nevertheless, the term is commonly used to describe a wide range of field operations and philosophical approaches that focus on two primary outcomes: the restoration of soil health, including carbon capture and storage, and the reversal of biodiversity loss [32].

3.1 Increased soil carbon to improve soil health

Soil is an active storage pool that can hold nearly three times as much carbon as the upper atmosphere. The loss of organic matter in the soil (SOC) contributes significantly to soil degradation. Studies have demonstrated that increasing SOC improves soil fertility, aeration, water infiltration, structure, and water retention. In addition, it has been recognized as a means to mitigate the impacts of climate change. The "4 per 1000" action, introduced by the French government at the 21st Paris Climate Conference (COP), proposes that an annual increase of 0.4 percent SOC in the top 30–40 cm of soil in all land uses could effectively absorb a substantial amount of CO2 emissions resulting from human activity. This approach also brings additional benefits such as improving soil health and enhancing food security [27]. To accomplish this objective, participants are encouraged to adopt management practices that enhance SOC sequestration. Regenerative farmers can use the Haney test to assess the health of their soils [33]. One of the core objectives of RA is to increase soil organic carbon (SOC) levels, which is crucial for soil health and biodiversity. Studies have shown that RA practices can significantly increase SOC levels, although the extent of this increase varies widely [34]. Improved soil health, in turn, supports a diverse range of soil organisms, which are essential for nutrient cycling and plant health [7, 34]. Regenerative agriculture promoted organic matter in the soil, which is crucial for further scientific work on soil health and climate mitigation [5, 35–37]. RA improves soil health by increasing total soil carbon (TSC), soil organic matter (SOM), total soil nitrogen (TSN), total soil phosphorus, calcium, and sulfur [38]. Research conducted on walnut cultivates in Spain found that enterprises employing organic modifications, enduring organic covers, and no-till actions performed better in terms of improving soil condition and increasing soil organic carbon (SOC) than farms that implemented fewer regenerative agriculture practices [39]. The SOC response of perennial crop rotation systems was higher than that of continuous annual and multi-crop annual systems, and the mean percentage shift in SOC was larger in no-till methods than in traditional till systems [40]. This demonstrates that canopy farming may not provide the same benefits for SOC as a mix of regenerative measures, cover cropping, crop rotation, no-till, and greater perennialization. According to a study on the transformation of deteriorated cropland to multi-species grass rotation [41] the adoption of regenerative tactics, such as no-till, no chemical fertilizers, biocides, holistic planned grazing, and the addition of other native plant species, had a significant positive impact on carbon storage over a 20-year period. Regenerative scoring matrix based on several regenerative system studies [36]. The findings showed that regenerative outcomes, including SOM, fine particle organic matter, and total soil carbon, improved with higher regeneration matrix scores. Overall, regenerative agricultural techniques are widely acknowledged to improve soil health and provide additional environmental benefits [36]. For example, tilling decreases soil erosion and promotes water penetration into soils. Cover crops helps to reduce water pollution, diverse crop rotations reduce pesticide consumption, and excellent grazing methods protect water supplies and increase vegetation [42]. The Planetary Health concept takes into account the planetary biogeochemical boundaries that create problems for ecosystems, such as global warming, air pollution, and changes in carbon and nitrogen cycles. Regenerative agriculture practices can improve soil health, combat global warming, and address agriculture-related planetary health issues by promoting plant-based diets (organic-based diets without fertilizers, pesticides, or pathogens) to reduce antibiotic resistance and greenhouse gas emissions, which can improve ecosystem and human health [18].

3.2 Land maxing in context of RA to improve soil health

It is widely recognized that increasing family income is crucial for obtaining better seeds, fertilizers, agrichemicals, labor, and extension services that contribute to staple food crop production [43]. In Cameroon, a three-step method has been developed to bridge yield gaps by combining the use of fertilizer trees to enhance soil fertility, generating revenue from local enterprises and industries, and diversifying farmers' fields with improved cultivars of culturally significant food and non-food plants [44, 45]. This project stands out for its grassroots approach, focusing on socially modifying new tree crops that yield traditional and culturally significant food and non-food items for village consumption. It also stimulates the creation of cottage industries, promotes local and regional trade innovation, and has the potential to generate new global products that can be integrated into rural development programs [46]. These advancements create fresh employment and business opportunities and contribute to revenue production. The comprehensive goal of this program is to address the growing environmental risks and global changes resulting from the decades-long neglect of the interdependence among economic, social, climate, and ecological drivers described by Pascal Peduzzi [47].

Improved land management not only benefits terrestrial environments but also reduces harm to marine habitats and stream siltation. Using low-tech solutions suitable for isolated rural communities, like those in Cameroon, can significantly minimize the environmental, social, and economic trade-offs typically considered unavoidable. Scaling up these solutions to reach new communities and expanding to different agroecosystems would lead to broader benefits [48]. Land Maxing, which simultaneously addresses production and social issues related to agricultural production, tackles the cycle of land deterioration and social hardship while also preserving wildlife. This is achieved by restoring ecosystem functionality, generating revenue from native tree crops, and providing well-forested alternative habitats for animals on profitable farmland and areas freed from agriculture. Additionally, Land Maxing enhances the environmental value of highly productive agricultural land by increasing the remaining woody waste for carbon sequestration. Therefore, Land Maxing surpasses the concept of "land sharing" [44] by encompassing social and commercial development, income generation, and agricultural and environmental reform, building on the concept of "landesque capital" [49]. Ultimately, Land maximization meets the needs of both animals and the two fundamental human requirements: food and an improved standard of living [44].

4 Regenerative agriculture practices to sustain ecology by boosting biodiversity.

Agricultural operations have a severe impact on biodiversity [50–52]. RA practices involve lowering inputs that are detrimental to biodiversity and diversifying farm species through the use of agriculture cover crops, perennial plants, and crop rotations. These practices enhance soil condition, which in turn boosts microbial biodiversity [4, 5, 29, 36, 50] ultimately sustaining ecology.This involves employing regenerative farming techniques to enhance the soil's microbiomes, as well as promoting above-ground biodiversity, ultimately contributing to the development of more environmentally sustainable societies. While regenerative agriculture has been shown to sustain biodiversity at multiple levels (including intraspecies, species, communities, and ecosystems), further research is needed to assess its impact across trophic levels and species. RA practices contribute to biodiversity conservation and the provision of ecosystem services. In tropical regions, agroforestry systems that incorporate nitrogen-fixing and indigenous tree species can restore soil fertility, enhance agroecosystem functions, and provide wildlife habitat [45]. These systems support natural predators, reducing the need for chemical pest control and promoting a balanced ecosystem. In contrast, temperate industrial farming often relies heavily on monocultures and chemical inputs, which can lead to biodiversity loss and ecosystem degradation [5, 53].

Agricultural diversification does not have a significant impact on crop yields. However, it improves biodiversity, pest control through pollination, and soil health effects such as enhanced fertility and water regulation [54]. Second-order meta-analyses assessments support these findings. Farms that adopt regenerative agriculture practices, including crop and non-crop diversification and organic amendments, better sustain diversity and may experience increased ecological benefits. Research on regenerative systems has shown notable increases in biodiversity. Regenerative almond systems, in particular, have been found to be advantageous for invertebrate and microbial ecosystems in the soil. Regenerative soils have significantly higher levels of total microbe biomass, total bacterium biomass, gram-positive bacteria, and actinobacteria compared to conventional soils. There is also an increase in the richness and variety of invertebrates [55]. Crop rotations in monocropping systems have diminished or been suppressed, resulting in a homogeneous landscape at any given time. In contrast, diverse crop rotations, which involve longer cycles and a wider range of crop types, gradually generate heterogeneity.

Studies have shown that crop rotations enhance the diversity of soil microbes [56] and ground beetles [57], while cover crops significantly improve biological pest and disease control [58]. A meta-analysis study reported crop diversification impact on rural wildlife, according to the results crop rotation and cover crops boosted 37% (16–62%) and 21% (17–25%) higher levels of biodiversity, respectively. Consequently, organic farms typically exhibit higher levels of biodiversity compared to traditional farms [59–62]. However, focusing solely on organic agricultural systems overlooks important elements and underutilizes the potential for biodiversity in agroecosystems [63]. Furthermore, environmental intensification can lead to increased agricultural yields. Intensive pasture management, with high cattle populations and fertilizer usage, has resulted in significant losses in plant communities, which subsequently impact arthropods and agricultural birds [64]. Conversely, unfertilized grasslands and silvopastoral cattle structures have been found to harbor high levels of biodiversity, with intensive grazing or mowing necessary to prevent tree invasion (e.g., in boreal [65], temperate [66], and tropical climates [67]. Global research has demonstrated that the impacts of grazing activities on species diversity and abundance vary depending on scale, taxonomic category, climate, and grazing extent [68]. A worldwide meta-analysis of grazing regimes indicated that grazing has a detrimental effect on plant and vertebrate abundance, as well as invertebrate diversity [69]. However, another meta-analysis study reported that low and moderate grazing intensities had positive impacts on plant and soil microbial diversity, which declined with high grazing intensity [70]. Not all taxa exhibited the same pattern in 70 study: arthropods consistently decreased with grazing due to reduced ground cover and plant biomass, resulting in less shelter. Additionally, a study on rewilding systems managing domestic or wild herbivore populations at densities no greater than 1.5 times the carrying capacity of the ecosystems found positive impacts of grazing on arthropods in five European countries [71]. This suggested that pastures can support high levels of biodiversity when managed to emulate grassland conditions. Moreover, it is recommended to leave grasslands unfertilized and multiply the carrying capacities of ecosystems (defined as the net primary productivity (NPP) of vegetation) by the rate at which above-ground biomass is utilized through grazing, potentially adjusted for slope as demonstrated [72]. Finally, by following regenerative agriculture practices, the soil can function as a living ecosystem. This involves employing regenerative farming techniques to enhance the soil's microbiomes, as well as promoting above-ground biodiversity, ultimately contributing to the development of more environmentally sustainable societies. While regenerative agriculture has been shown to sustain biodiversity at multiple levels (including intraspecies, species, communities, and ecosystems), further research is needed to assess its impact across trophic levels and species.

4.1 Role of trees in agroecosystems to boost biodiversity

Trees play an important role in agroecosystems, creating habitat for a variety of creatures. In Brazil's Atlantic Forest, selective management of regenerating communities in agroforestry systems using African mahogany has been proven to improve ecosystem services. Treatments that included selective management resulted in increased biomass output, nutrient buildup, and the colonization of native shrub and tree species. Baccharis dracunculifolia and Vismia guianensis are among the plants that considerably contribute to nutrient stocks and provide ecosystem services including pollination and pest control [73]. Similarly, in the tropics, the integration of nitrogen-fixing trees and indigenous tree species into smallholder farming systems has been found to restore soil fertility and agroecosystem functions. These trees not only improve soil health but also provide wildlife habitat, supporting natural predators that help control herbivores and pathogens. This approach promotes biodiversity conservation and creates productive, environmentally friendly farming systems that enhance food security and alleviate poverty [45]. The establishment and natural regeneration of native trees in agroforestry systems are essential for creating functional agroecosystems. In the Paraguayan Atlantic Forest, studies have shown that the survival and growth rates of native tree species vary depending on the agronomic system and plantation type. Species like Cedrela fissilis and Cordia trichotoma have demonstrated different survival and growth patterns, indicating that species selection is crucial for successful regeneration. Natural regeneration of species such as C. trichotoma and Peltophorum dubium further contributes to the biodiversity and resilience of these systems [74].

The functional traits of plants, including trees, are pivotal in determining their role in agroecosystems. In the Colombian Andes, semi-domesticated Phaseolus beans are managed by indigenous farmers for their unique functional traits, such as perenniality and resistance to pests. These traits allow the beans to thrive in various ecological niches, including low-intervention areas like hedges and fallow plots. The management practices associated with these beans enhance the resilience of agroecosystems and contribute to ecosystem services such as soil conservation and crop protection [75]. Advances in functional ecology emphasize the importance of plant functional traits in ecosystem processes and services. Sustainable agricultural practices that expand plant biodiversity can improve soil properties and support vital ecosystem services, including food production and climate change mitigation. Understanding the links between plant traits and soil properties is essential for the ecological intensification of agriculture [76]. Figure 3. Represents regenerative agriculture impact on biodiversity to sustain ecology.

4.2 IPBES, CBD and CIAT response for regenerative agriculture.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), CBD (Convention on Biological Diversity) and CIAT (The International Center for Tropical Agriculture) response for RA as follows.

1. (IPBES) Viewpoint about RA: IPBES underscores biodiversity-friendly and ecosystem service-enhancing agricultural practices. Regenerative agriculture goals relate to IPBES, focusing on restoring soil health and biodiversity while

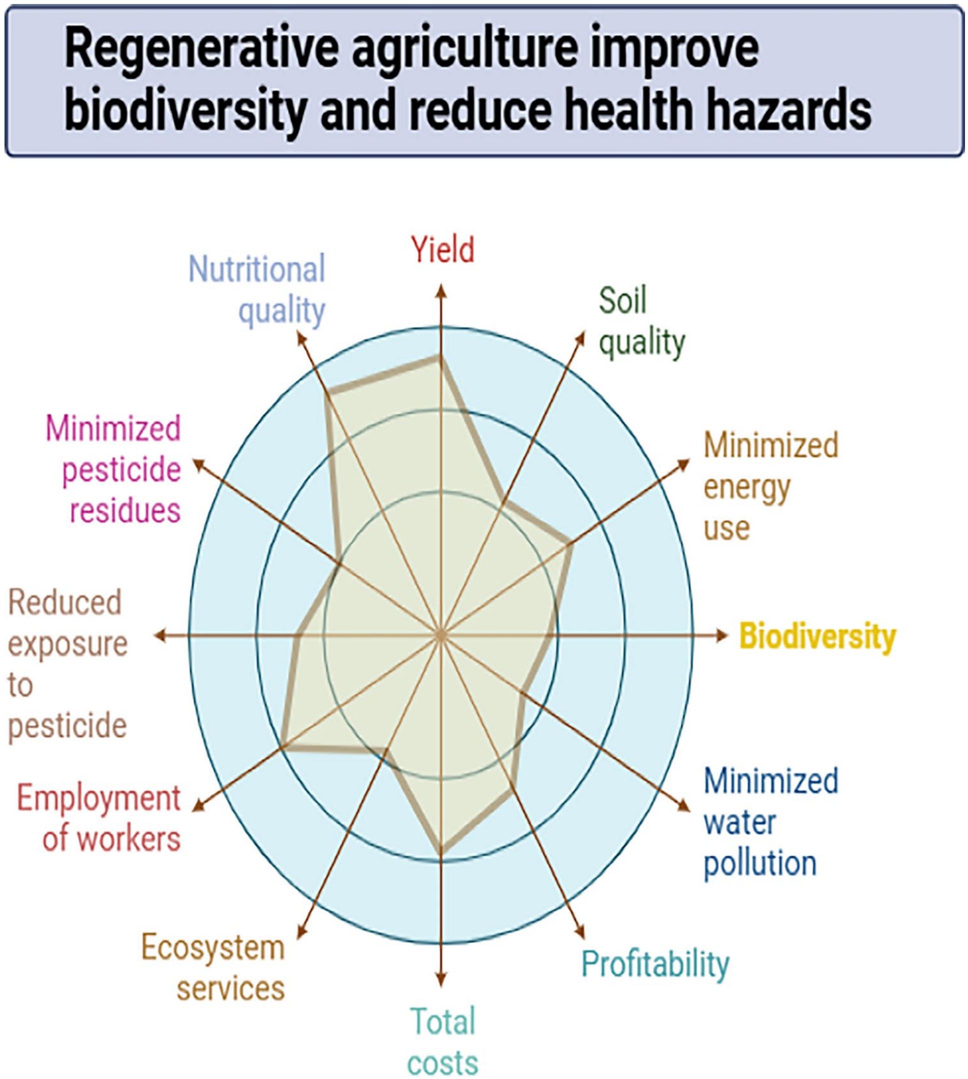

Fig. 3 Regenerative agriculture impact on biodiversity to sustain ecology

improving ecosystem resilience. The analysis helps the preservation of ecosystems and essential ecosystem providers that hold our globe moving simultaneously. IPBES emphasizes the need for mainstreaming biodiversity into sectoral policies to achieve these goals [77].

2. CBD (Convention on Biological Diversity) Opinion about RA: The CBD promotes farming practices that help to maintain and sustainable use of Benefit-sharing biodiversity. This is because regenerative agriculture aligns with goals of the CBD by focussing on farming practises that replenish soil health, increase biodiversity and decrease the ecological harm caused through (non) conventional agricultural means. Contributes to the broader objectives of the CBD by promoting sustainable land management. CBD's post-2020 global biodiversity framework advocates for increased conservation efforts and sustainable use of biodiversity [77].
3. The International Center for Tropical Agriculture (CIAT) opinion about RA. Purely: At CIAT, increasingly warm to regenerative agriculture because it fits perfectly with our interest in sustainable production practices and the conservative use of ecosystems. CIAT's work is closely aligned with the principles of regenerative agriculture an approach that aims to boost soil fertility, biodiversity and promote sustainable land use. The methodology is considered good for sustainable agricultural growth especially in tropical areas and helps to combat water scarcity by directly utilizing sea water.

5 Social, economic, and political policies for regenerative agriculture implementation

The socio-economic benefits of RA are particularly pronounced in tropical and subtropical regions. Diversified farming systems that include agroforestry and integrated livestock can improve food and nutritional security, alleviate poverty, and provide sustainable income sources for smallholder farmers [45]. In temperate regions, RA practices can also enhance farmer profitability by reducing input costs and improving soil health, although the transition may require significant changes to existing farming systems [5, 27]. The implementation of regenerative agriculture methods is most beneficial for agricultural systems and communities that have the highest potential for scalability. RA adoption requires favorable enabling conditions, including legislation, farmer adoption, and the application of best practices over the appropriate time frames [78]. To increase adoption rates, it is crucial to provide institutional, financial, and policy support. Extensive research has already been conducted on farmers' decision-making processes when adopting regenerative agriculture practices. Moving forward, research should focus on combining this knowledge with the dissemination of accurate information about the potential effects of different regenerative farming methods, whether used individually or in combination with other adaptations. Climate policy and its relationship to regenerative agriculture are often overlooked in policy frameworks, such as when discussing the need to balance food and fuel production. By incorporating practices like no-till farming [79], fallow season cover crops [80], and livestock grazing on crop fields [81], regenerative farmers have been able to reduce fertilizer costs and increase crop prices by selling directly to customers as feed or seed and earning organic premiums. They have also found alternative sources of income from their fields, such as grazing cover mixtures alongside cattle. The profitability of a corn field is strongly linked to the amount of organic matter in the soil and negatively correlated with soil density, rather than with grain yields [5]. North America shows the highest potential for total carbon storage (0.17–0.35 PgC/y), followed by South Asia and Europe (0.11–0.23 PgC/y), highlighting the significant potential in these heavily farmed regions [82]. This study examined the carbon sequestration capacity of farmland soils globally. South Asia and North Africa have the greatest potential for carbon dioxide storage per hectare, while the United States, India, China, and Russia have the highest overall potential for carbon dioxide storage annually when considering national levels of cropland and average annual growth [82]. In order to fully realize the benefits of regenerative agriculture, it is crucial to consider these high carbon storage sites, with a particular focus on soils damaged by previous intensive agriculture. Economic benefits of regenerative agriculture on former yields and found that orchards practicing regenerative agriculture were twice as profitable as conventional orchards [36]. This increased profit was attributed to the success of regenerative farms, which effectively combined multiple regenerative practices into a functional farm system. Implementing regenerative agriculture can address various socioecological issues, such as biodiversity loss, agricultural pollution, global warming, chronic human health issues, mental health problems, and improving the social well-being of farmers [5]. Additionally, corn and cattle grazing farms in the Midwest that practiced regenerative agriculture demonstrated better soil health metrics, increased biodiversity, and reduced pest damage compared to conventional systems [5]. Furthermore, the farmer yield was twice as high in regenerative agriculture systems. Enhancing soil health through regenerative farming practices promotes ecological equity by reducing the risk of pesticide exposure for farmers and agricultural laborers. Additionally, regenerative farming may require more labor, but these costs can be offset by a decrease in the use of agrochemical inputs, resulting in thriving rural economies and ecological communities. Increasing microbial and nutritional diversity contributes to disease prevention and resistance in both soils and humans. The key to increasing yields while minimizing the use of fossil fuels and agrochemicals is to enhance soil organic matter and biodiversity. This not only improves farm profitability and rural incomes, but also provides customers with more nutritious meals. To maximize the socio-ecological benefits of regenerative agriculture practices, education and training programs should be developed to improve the agricultural literacy of medical practitioners and incorporate soil health principles. Research projects should also investigate the epidemiological relationships between soil properties and health outcomes in farms and communities. In contrast to conventional agriculture, greater emphasis should be placed on principles of soil health, ecological diversity, and the adoption of regenerative farming practices and technologies that promote the well-being of humans, livestock, and the natural environment. Table 2 depicted overview of benefits of regenerative Agriculture practices on farming community and ecosystem. Finally, in order to meet the challenges of population growth, persistent poverty and hunger, resource depletion, and global warming, global food production needs to quadruple while also improving the long-term sustainability and adaptability of farming systems. Only through collaborative efforts involving farmers, national and international researchers, policymakers, businesses, and development partners can this demand be met. This collaborative

Table 2 Overview of Regenerative Agriculture Benefits

Soil health	Increasing organic matter, improving soil structure, and encouraging microbial diversity are three ways that regenerative agriculture techniques promote soil health. in order to produce food in a sustainable manner, improved soil fertility, nutrient cycling, and water retention result from RA
Biodiversity conservation	RA promotes biodiversity protection by combining a variety of crops, rotational grazing, and habitat remediation. By fostering natural pest management, lowering the need for pesticides, and providing habitats for native species, it increases the resilience of ecosystems
Water quality and conservation	Improved water infiltration, less soil erosion, and less pollutant runoff into water bodies are all made possible by techniques like cover crops and less tillage. Water conservation is also encouraged by RA by using watershed management and effective irrigation techniques
Climate change mitigation	By storing carbon in the soil and absorbing CO2 from the atmosphere, regenerative agriculture helps to slow down global warming. Improved soil structure and decreased susceptibility to droughts, floods, and other climate-related pressures also increase resistance to extreme weather events
Food security and local economies	RA reduces reliance on long-distance food transportation and external inputs by encouraging diverse farming systems and local food networks, hence improving food security. In addition to bolstering local economy, this promotes community resilience and small-scale farming
Resilient agroecosystems	Agroecosystems are more resilient to environmental stresses and shocks when they are managed holistically, as in regenerative agriculture. It assists farmers in long-term risk mitigation, condition adaptation, and productivity maintenance by enhancing ecosystem services and functions

approach should involve target communities and national governments in developing sustainable solutions that improve the socio-economic well-being of rural communities. Table 3 illustrates the policies for implementation of RA Practices. Figures 4 and 5 represent socio-ecological and economic impact of regenerative practices in society.

6 Regenerative agriculture, while beneficial in many ways, can face challenges from various environmental, economic, and social policies that may hinder its adoption or effectiveness.

Following is a breakdown of some of these potential challenges:

Regenerative agriculture (RA) is increasingly recognized for its potential to improve soil health, enhance biodiversity, and contribute to climate resilience. However, its adoption and effectiveness can be significantly hindered by various environmental, economic, and social policies. These challenges and the implications for the broader adoption of RA practices are as follows.

6.1 Environmental challenges

One of the primary environmental challenges to the adoption of RA is the variability in its effectiveness across different agroecosystems. Practices such as minimum tillage, residue retention, and cover cropping have been shown to improve soil carbon and crop yield in certain climatic zones and soil types, but these benefits are not universally applicable [27]. Additionally, the excessive use of synthetic chemicals in conventional farming can lead to biodiversity loss and ecosystem degradation, which RA aims to mitigate. However, transitioning away from these chemicals requires significant changes in farming practices and can be met with resistance from farmers accustomed to conventional methods [27].

6.2 Economic challenges

Economic barriers are a significant impediment to the widespread adoption of RA. Many farmers are reluctant to adopt RA practices due to a lack of empirical evidence on their profitability and long-term benefits [27]. The initial costs associated with transitioning to RA, such as purchasing new equipment or altering existing farming systems, can be prohibitive. Furthermore, the lack of standardized definitions and bioeconomic assessments of RA complicates the understanding and application of these practices, making it difficult for farmers to justify the investment [7].

Table 3 Regenerative Agriculture implementation Policies

Political	Subsidies for regenerative practices	Farmers using regenerative agriculture are eligible for government subsidies designed to promote adoption and aid in the transition process
	Research Funding	Government funding to be used in regenerative agriculture research and development, encouraging creativity and information exchange
	Land Use Regulations	Application of laws to preserve and improve agricultural land, including soil conservation and zoning laws that stop urban sprawl
	Carbon Pricing	Carbon pricing schemes should be put in place to encourage farmers to use regenerative farming methods that store carbon and cut emissions
Social	Education and Training Programs	Building workshops and educational programs to teach farmers and communities the methods and concepts of regenerative agriculture
	Community-Based Initiatives	Encouragement of cooperation and information sharing among stakeholders through community-led projects that advance regenerative agriculture
	Access to Land and Resources	Laws that guarantee marginalized and small-scale farmers who want to engage in regenerative agriculture fair access to land, water, and other resources
Economic	Market Incentives	Economic incentives for sustainability through the development of markets and certification schemes that compensate farmers for implementing regenerative methods
	Farm-to-Table Networks	Establishing local food networks, which link regenerative farmers and consumers directly and support regional economies and sustainable agriculture
	Financial Assistance Programs	Financial incentives such as grants and low-interest loans are offered to farmers in order to facilitate their shift towards regenerative agriculture practices
	Value-Added Products	Promoting the development of value-added products from foods cultivated sustainably, opening up new markets and boosting farm income

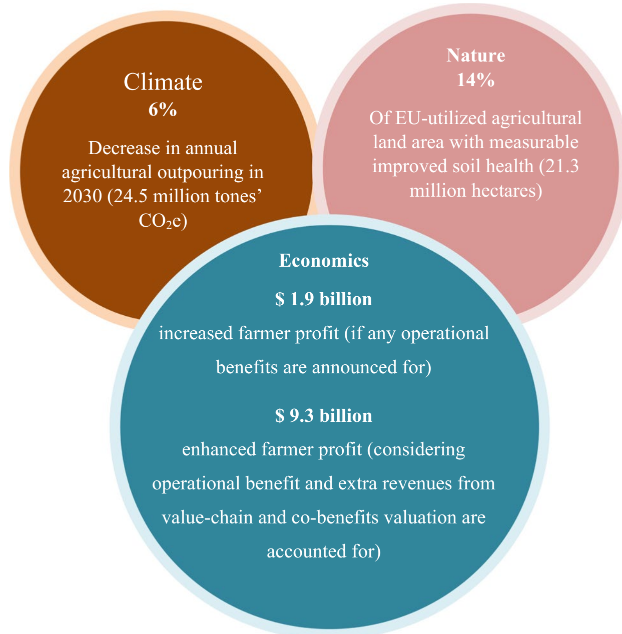

Fig. 4 Socio-economic impact of regenerative Agriculture. (Source world economic forum https://www3.weforum.org/maintenance/public.htm)

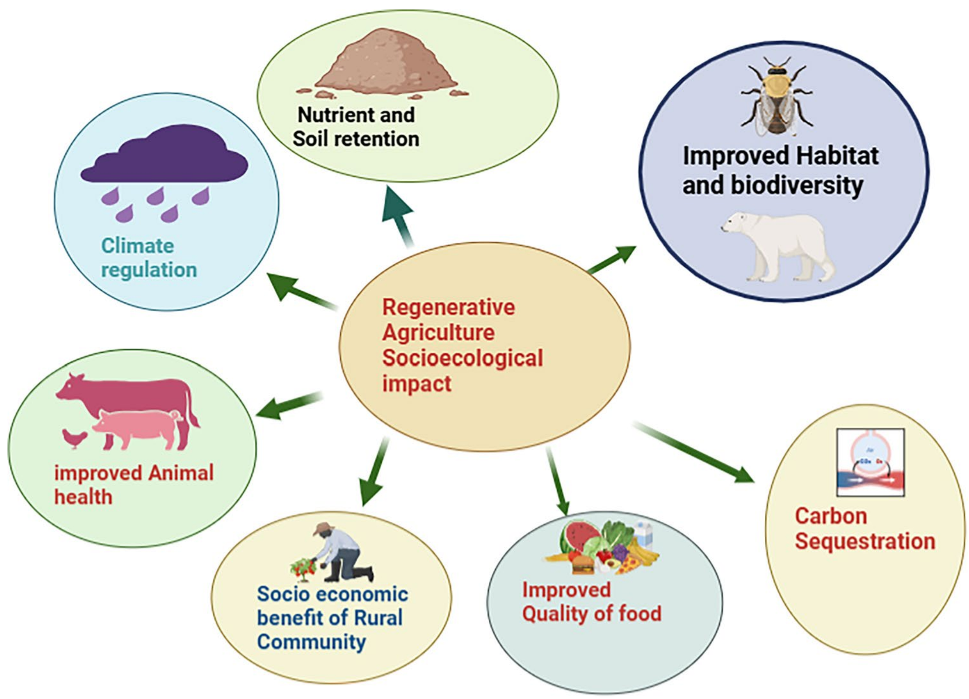

Fig. 5 Socioecological impact of regenerative agriculture

6.3 Social and policy challenges

Social and policy-related challenges also play a crucial role in hindering the adoption of RA. In the U.S., for example, transforming agriculture to a regenerative system requires a shift in values, beliefs, and worldviews that support such transformation. This involves creating traction for ecological improvements on farms while decreasing the friction that works against them [83]. The current agricultural policies often favor conventional farming practices, providing subsidies and support that do not align with the principles of RA. Additionally, there is a mismatch between academic and policy interest in RA and the social and human motivating benefits that drive farmers to adopt these practices [9].

6.4 Case studies and regional variations

The implementation of RA varies significantly across different regions. In Poland, Czechia, and Slovakia, for instance, RA is often identified with biological farming, and its practices are infrequently implemented, usually only at large farms [83]. In Australia, the development of a certification scheme for RA practices faces challenges similar to those encountered by the organic agriculture industry, highlighting the need for a holistic approach to labeling and certification [84].

6.5 Funding and research

Limited funding and research opportunities for regenerative agriculture can restrict innovation and the development of effective practices, making it harder for farmers to transition to regenerative methods.

6.6 Training and education

A lack of access to education and training programs focused on regenerative agriculture can be a barrier. Without adequate support and knowledge, farmers may be hesitant to adopt regenerative practices.

6.7 Consumer preferences and awareness

Social policies that do not promote awareness or support for regenerative agriculture can impact market demand. If consumers are not educated about the benefits of regenerative practices, there may be less pressure on policymakers and businesses to support these methods.Table 4. Illustrates examples from public, private, and nonprofit sectors, as well as academic, non-academic, and non-governmental organizations that have been showing successful cases on regenerative agriculture in their trials or field scale interventions.

6.8 Recommendations for future research and policy

To overcome these challenges, it is recommended to implement rigorous long-term farming system trials to compare conventional and RA practices. This will help build a robust evidence base to inform growers and policymakers about the benefits and mechanisms associated with RA on regional scales [27]. Additionally, promoting a transdisciplinary approach that integrates socioeconomic outcomes and local knowledge with established scientific knowledge can enhance the understanding and application of RA [7]. Policies should also focus on creating supportive environments for RA through education, social learning, and polycentric governance [85]. RA several challenges, including the lack of a standardized definition and limited bioeconomic assessments [7, 86]. There is also a need for more research to validate the long-term benefits of RA practices and to develop robust assessment tools [7, 34]. The integration of advanced analytical methods, such as artificial intelligence and machine learning, could enhance the evaluation of RA outcomes [7].

7 Linkage of regenerative agriculture (RA) with nature's contributions to people (NCP) and sustainable development goals (SDGs)

Regenerative Agriculture (RA) is an approach to farming that emphasizes the restoration and enhancement of ecosystem health, biodiversity, and soil fertility. Recently, the concept of Nature's Contributions to People (NCP) has gained traction globally, highlighting the benefits that ecosystems provide to human well-being. This section will explain the linkage between RA and NCP, and how this relationship can contribute to achieving the Sustainable Development Goals (SDGs) by 2030. Additionally, s the potential burdens and constraints associated with RA.

7.1 Linkage of RA with NCP

RA practices such as improved cropland management, agroforestry, and integrated water management have been shown to positively impact NCP. These practices enhance soil health, increase biodiversity, and improve water

Table 4 Public, private, and nonprofit sectors, as well as academic, non-academic, and non-governmental organizations that have been showing successful cases on regenerative agriculture in their trials or field scale interventions

Public sector	Government Initiatives in Poland, Czechia, and Slovakia	In tIn these countries, regenerative agriculture is often identified with biological farming. The conscious implementation of its practices is infrequent but is seen in large farms. This indicates a growing interest and initial implementations supported by public policies aimed at sustainable food production [120]
Public sector	USDA (United States Department of Agriculture)	Through programs like the Conservation Stewardship Program (CSP), USDA supports regenerative practices such as cover cropping and rotational grazing on farms across the U.S
Private sector	General Mills Initiative:	General Mills has committed to advancing regenerative agriculture on 1 million acres by 2030. They have partnered with farmers to create an enabling environment for RA adoption through education, coaching, community building, and monitoring soil and wildlife. This initiative also explores ecosystem service markets, demonstrating a significant corporate investment in RA [121]
Private sector	Patagonia	Known for its commitment to sustainable practices, Patagonia supports regenerative agriculture through its food supply chain and the Regenerative Organic Certification for its products
Private sector	Corporate Interest and Market Integration	The rapid increase in corporate interest in regenerative agriculture is evident, with companies integrating RA practices into their supply chains. This includes the use of cover crops, reduced tillage, and integrating livestock, which are promoted as part of sustainable business practices [4, 6]
Academic organizations	Research and Framework Development**:**	Academic institutions have been pivotal in defining and assessing regenerative agriculture. For instance, a conceptual framework for evaluating the bioeconomic outcomes of RA in mixed farming settings in Australia has been developed. This framework promotes a transdisciplinary approach, integrating data and stakeholder engagement to assess RA practices comprehensively [7]
Academic organizations	Empirical Studies and Long-term Trials	Rigorous long-term farming system trials are recommended to compare conventional and RA practices. These trials aim to build knowledge on the benefits and mechanisms associated with RA on regional scales, providing an evidence base for growers and policymakers [27]
Academic organizations	The Land Institute	Based in Kansas, it conducts research on perennial crops and polycultures that support regenerative agriculture principles and improve soil health
Non-academic organizations	Kiss the Ground	This organization works on educating farmers and the public about regenerative agriculture through outreach and advocacy, and highlights successful field trials and case studies
Non-governmental organizations (NGOs)	World Wildlife Fund (WWF)	WWF supports regenerative agricultural practices as part of its broader conservation efforts and provides case studies demonstrating their effectiveness in enhancing biodiversity and ecosystem services. Non-governmental organizations (NGOs) have been strong advocates for regenerative agriculture, promoting practices such as crop residue retention, cover cropping, and reduced tillage. These practices are central to the canon of good agricultural practices and are supported by civil society to address soil health and biodiversity [86]

retention, which in turn contribute to various NCPs like food and water security, climate regulation, and cultural services [87–89]. For instance, improved soil management practices can enhance soil organic carbon content, reduce soil erosion, and increase soil fertility, thereby supporting both ecosystem services and agricultural productivity [87, 88].

7.2 Contribution to SDGs

The integration of RA with NCP can significantly contribute to the achievement of multiple SDGs. Improved land management practices associated with RA can help achieve SDG 2 (Zero Hunger) by increasing food security and SDG 13 (Climate Action) by enhancing carbon sequestration and reducing greenhouse gas emissions [86, 87]. Additionally, RA practices that promote biodiversity and ecosystem health can support SDG 15 (Life on Land) by preventing land degradation and promoting sustainable land use [88, 89].

In Nepal, for example, NCPs have been found to contribute positively towards the achievement of 12 SDGs. However, the decline in NCPs due to land-use change, over-exploitation, and climate change poses a significant challenge. Integrating Indigenous knowledge and local practices has been effective in improving NCPs and contributing to local livelihoods, highlighting the importance of community-based approaches in RA [88].

7.3 Burdens and constraints

Despite the potential benefits, there are several burdens and constraints associated with RA. One major challenge is the initial cost and effort required to transition from conventional to regenerative practices. Farmers may face financial and technical barriers, and there may be a lack of access to necessary resources and knowledge. Additionally, some interventions, such as bioenergy production and afforestation, can have negative impacts on both NCPs and SDGs if not managed properly [87].

Poorly managed soils can contribute negatively to both NCPs and SDGs, emphasizing the need for careful soil management. Priorities for soil management should include protecting healthy soils from degradation, enhancing soil biodiversity and health in managed soils, and restoring degraded soils to full health [89, 90]. Without proper management, the potential of soils to contribute to sustainable development cannot be fully realized.

8 Conclusion and future prospects

Regenerative agriculture main objective is to improve soil health, biodiversity, and ecosystem resilience while also enhancing carbon sequestration and water retention. Its socioecological impact includes fostering more sustainable and resilient farming practices, supporting rural community, and mitigating the effects of climate change. Regenerative approaches facilitate the sequestration of atmospheric carbon dioxide and its storage in the soil, helping to reduce greenhouse gas emissions. Additionally, these measures strengthen the soil's resilience to extreme weather events by increasing soil organic matter, promoting nitrogen cycling, and improving water infiltration. Methods such as crop rotation, cover crops, and low tillage are used to increase soil fertility in regenerative agriculture. This results in more nutrients being available, less erosion, and increased water storage capacity in the soil, leading to higher crop yields and financial gains for farmers. Furthermore, regenerative agriculture plays a crucial role in preserving ecology and biodiversity. By encouraging diverse crop rotations, creating wildlife habitats, and reducing the use of industrial fertilizers and pesticides, regenerative approaches helps to protect endangered species and natural ecosystems. From a socio-ecological standpoint, regenerative agriculture offers numerous advantages. It can improve the standard of living for small-scale farmers by reducing input costs, increasing crop yields, and providing diversification opportunities. Local and regional markets are also prioritized in regenerative techniques. The future prospects for regenerative agriculture are promising. Scaling up and implementing its techniques worldwide can lead to a more robust and sustainable food system. However, in order to fully realize its benefits, consumers, farmers, researchers, and governments must collaborate. Investment in infrastructure, education, and research is essential to encourage the widespread adoption of regenerative methods. Regenerative agriculture presents a comprehensive solution to urgent problems such as soil erosion, biodiversity loss, and climate change. It has the potential to reduce climate change, improve soil health, promote biodiversity, and generate economic benefits. By embracing regenerative techniques, we can create the conditions for a more sustainable and resilient future.

Acknowledgements The work is supported by Shandong Agricultural university. We are very grateful to National Major Agricultural Science and Technology Program (NK202218080314), Shandong Province key research and development Program (2021LZGC014-2) National Nature Science Founds (32172115), and National Modern Agricultural Technology Industry System (CARS-02-21) for providing funding.

Author contributions AS, HL and AU wrote the MS. YS and BN revised the MS. JZ critically read and improved the MS.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests All authors declared that they have no conflict of interest.

References

1. United Nations. World population prospects 2019. Department of economic and social affairs, population division. 2021.
2. Pingali PL. Green revolution: impacts, limits, and the path ahead. Proc Natl Acad Sci USA. 2012;109(31):12302–8.
3. Asbjornsen H, Hernandez-Santana V, Liebman M, Bayala J, Chen J, Helmers M, Ong CK, Schulte LA. Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. Renew Agric Food Syst. 2014;29(2):101–25.
4. Newton P, Civita N, Frankel-Goldwater L, Bartel K, Johns C. What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. Front Sustain Food Syst. 2020;4:194.
5. LaCanne CE, Lundgren JG. Regenerative agriculture: merging farming and natural resource conservation profitably. PeerJ. 2018;26(6): e4428. https://doi.org/10.7717/peerj.4428.PMID:29503771;PMCID:PMC5831153.
6. O'Donoghue T, Minasny B, McBratney A. Regenerative agriculture and its potential to improve farmscape function. Sustainability. 2022;14(10):5815.
7. Jayasinghe SL, Thomas DT, Anderson JP, Chen C, Macdonald BCT. Global application of regenerative agriculture: a review of definitions and assessment approaches. Sustainability. 2023;15:15941.
8. Lal R. Regenerative agriculture for food and climate. J Soil Water Conserv. 2020;75(5):123A-124A.
9. Burns A. Regenerative agriculture: farmer motivation environment and climate improvement. Pol Quarter. 2021. https://doi.org/10.26686/pq.v17i3.7133.
10. Jeffery S, Abalos Rodriguez D, Prodana M, Bastos AC, van Groenigen JW, Hungate BA, Verheijen F. Biochar boosts tropical but not temperate crop yields. Environ Res Lett. 2017;12(5):053001.
11. Marsden T, Sonnino R. Rural development and the regional state: denying multifunctional agriculture in the UK. J Rural Stud. 2008;24:422–31.
12. Rodale R. Breaking new ground: the search for a sustainable agriculture. Futurist. 1983;1:15–20.
13. McClelland SC, Paustian K, Schipanski ME. Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis. Ecol Appl. 2021;31: e02278.
14. Perry JN. Regenerating agriculture: policies and practice for sustainability and self-reliance. London: Joseph Henry Press; 1995.
15. Gabel M. Ho-Ping: a world scenario for food production. Philadelphia: World Game Institute; 1979.
16. Rodale R. Learning to think regeneratively. Bull Sci Technol Soc. 1986;6:6–13.
17. McLennon E, et al. Regenerative agriculture and integrative permaculture for sustainable and technology driven global food production and security. Agron J. 2021;113(6):4541–59.
18. Montgomery DR, Rabinowitz P, Sipos Y, Wheat EE. Soil health: A common focus for one health and planetary health interventions. One Health. 2024;18:100673.
19. International Energy Agency: the future of petrochemicals. https://www.iea.org/reports/the-future-of-petrochemicals Accessed 5 Aug 2023.
20. Yale Environment 360: The plastics pipeline: a surge of new production is on the way. https://e360.yale.edu/features/the-plastics-pipeline-a-surge-of-new-production-is-on-the-way. Accessed 5 Aug 2023.
21. Stathatou PM, et al. Biomaterials and regenerative agriculture: a methodological framework to enable circular transitions. Sustainability. 2023;15(19):14306.
22. Friedlingstein P, Jones MW, O'Sullivan M, Andrew RM, Bakker DCE, Hauck J, Le Quéré C, Peters GP, Peters W, Pongratz J, Sitch S, Canadell JG, Ciais P, Jackson RB, Alin SR, Anthoni P, Bates NR, Becker M, Bellouin N, Bopp L, Chau TTT, Chevallier F, Chini LP, Cronin M, Currie KI, Decharme B, Djeutchouang L, Dou X, Evans W, Feely RA, Feng L, Gasser T, Gilfillan D, Gkritzalis T, Grassi G, Gregor L, Gruber N, Gürses Ö, Harris I, Houghton RA, Hurtt GC, Iida Y, Ilyina T, Luijkx IT, Jain AK, Jones SD, Kato E, Kennedy D, Klein Goldewijk K, Knauer J, Korsbakken JI, Körtzinger A, Landschützer P, Lauvset SK, Lefèvre N, Lienert S, Liu J, Marland G, McGuire PC, Melton JR,

Munro DR, Nabel JEMS, Nakaoka S-I, Niwa Y, Ono T, Pierrot D, Poulter B, Rehder G, Resplandy L, Robertson E, Rödenbeck C, Rosan TM, Schwinger J, Schwingshackl C, Séférian R, Sutton AJ, Sweeney C, Tanhua T, Tans PP, Tian H, Tilbrook B, Tubiello F, van der Werf G, Vuichard N, Wada C, Wanninkhof R, Watson A, Willis D, Wiltshire AJ, Yuan W, Yue C, Yue X, Zaehle S. Data discuss. 2021. J Earth Syst Sci. https://doi.org/10.5194/essd-2021-386.
23. Scott J. Climate change economics: carbon capitalism, regenerative agriculture, urban farming & beyond.
24. LaSalle TJ, Hepperly P. Regenerative organic farming: a solution to global warming. Rodale Institute, 2008; 1–13.
25. Sherwood S, Uphoff N. Soil health: research, practice and policy for a more regenerative agriculture. Appl Soil Ecol. 2000;15(1):85–97.
26. Lehmann J, Bossio DA, Kögel-Knabner I, Rillig MC. The concept and future prospects of soil health. Nat Rev Earth Environ. 2020;1:544–53. https://doi.org/10.1038/s43017-020-0080-8.
27. Khangura R, Ferris D, Wagg C, Bowyer J. Regenerative agriculture—a literature review on the practices and mechanisms used to improve soil health. Sustainability. 2023;15:2338.
28. Giller KE, et al. Regenerative agriculture: an agronomic perspective. Outlook Agric. 2021;50(1):13–25.
29. Schreefel L, Schulte RPO, de Boer IJM, Schrijver AP, van Zanten HHE. Regenerative agriculture the soil is the base. Glob Food Sec. 2020;26: 100404.
30. Hill CG. Returning the "three sisters"—corn, beans and squash— to Native American farms nourishes people, land and cultures. The Conversation. 2020.
31. Díaz De Otálora X, Epelde L, Arranz J, Garbisu C, Ruiz R, Mandaluniz N. Regenerative rotational grazing management of dairy sheep increases springtime grass production and topsoil carbon storage. Ecol Ind. 2021;125: 107484.
32. Rempelos L, et al. Innovative organic and regenerative agricultural production. MDPI. 2023;13:1344.
33. Ripplinger H. The impact of regenerative agriculture fertilization practices on soil health and chemical properties. Dakota: North Dakota State University; 2023.
34. Rehberger E, West P, Spillane C, McKeown P. What climate and environmental benefits of regenerative agriculture practices? an evidence review. Environ Res Commun. 2023;5:52001.
35. Ryals R, Silver WL. Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands. Ecol Appl. 2013;23:46–59. https://doi.org/10.1890/12-0620.1.
36. Demestihas C, Plénet D, Génard M, Raynal C, Lescourret F. Ecosystem services in orchards. A review. Agron Sustain Dev. 2017;37:12. https://doi.org/10.1007/s13593-017-0422-1.
37. Soto RL, Martinez-Mena M, Padilla MC, de Vente J. Restoring soil quality of woody agroecosystems in Mediterranean drylands through regenerative agriculture. Agric Ecosyst Environ. 2021;306: 107191. https://doi.org/10.1016/j.agee.2020.107191.
38. Fenster TLD, LaCanne CE, Pecenka JR, Schmid RB, Bredeson MM, Busenitz KM, et al. Defining and validating regenerative farm systems using a composite of ranked agricultural practices [version 1; peer review: 2 approved]. Research. 2021;10:115.
39. Soto RL, deVente J, Cuéllar Padilla M. Learning from farmers' experiences with participatory monitoring and evaluation of regenerative agriculture based on visual soil assessment. J Rural Stud. 2021;88:192–204.
40. McClelland SC, Paustian K, Schipanski ME. Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis. Ecol Appl. 2021;31: e02278.
41. Rowntree JE, Stanley PL, Maciel ICF, Thorbecke M, Rosenzweig ST, Hancock DW, Raven MR. Ecosystem impacts and productive capacity of a multi-species pastured livestock system. Front Sustain Food Syst. 2020. https://doi.org/10.3389/fsufs.2020.544984.
42. Ranganathan J, Waite R, Searchinger T, Zionts J. Regenerative agriculture: good for soil health, but limited potential to mitigate climate change. 2020. https://wri.org/insights/regenerative-agriculture-good-soil-health-limited-potential-mitigate-climate-change
43. Akumbole AK, Zakaria H, Adam H. Determinants of adoption of improved maize technology among smallholder maize farmers in the Bawku West district of the Upper East Region of Ghana. J Agric Extension. 2018;2(2):165–75.
44. Leakey RR. A re-boot of tropical agriculture benefits food production, rural economies, health, social justice. Nat Food. 2020;1:260–5.
45. Leakey RRB. The role of trees in agroecology and sustainable agriculture in the tropics. Annu Rev Phytopathol. 2014;52:113–33.
46. Degrande A, et al. GFRAS Good Practice Notes for Extension and Advisory Services Note 10. GFRAS. 2015.
47. Peduzzi P. The disaster risk, global change, and sustainability nexus. Sustainability. 2019;11(4):957.
48. Godfray HCJ, Garnett T. Food security and sustainable intensification. Philos Trans Royal Soc B. 2014;369(1639):20120273.
49. Blaikie P, Brookfield H. Land degradation and society. London: Routledge; 2015.
50. Kovács-Hostyánszki A, Espíndola A, Vanbergen AJ, Settele J, Kremen C, Dicks LV. Ecological intensification to mitigate impacts of conventional intensive land use on pollinators and pollination. Ecol Lett. 2017;20:673–89. https://doi.org/10.1111/ele.12762.
51. Sanchez-Bayo F, Wyckhuys KAG. Worldwide decline of the entomofauna: a review of its drivers. Biol Conserv. 2019;232:8–27. https://doi.org/10.1016/j.biocon.2019.01.020.
52. Stewart JAE, Butterfield HS, Richmond JQ, Germano DJ, Westphal MF, Tennant EN, et al. Habitat restoration opportunities, climatic niche contraction, and conservation biogeography in California's San Joaquin desert. PLoS ONE. 2019. https://doi.org/10.1371/journal.pone.0210766.
53. Elevitch CR, Mazaroli DN, Ragone D. Agroforestry standards for regenerative agriculture. Sustainability. 2018;10(9):3337. https://doi.org/10.3390/su10093337.
54. Tamburini G, Bommarco R, Wanger TC, Kremen C, van der Heijden MGA, Liebman M, et al. Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci Adv. 2020;6:eaba1715. https://doi.org/10.1126/sciadv.aba171.
55. Fenster TL, Oikawa PY, Lundgren JG. Regenerative almond production systems improve soil health, biodiversity, and profit. Front Sustain Food Syst. 2021;5:256.
56. Venter ZS, Jacobs K, Hawkins H-J. The impact of crop rotation on soil microbial diversity: a meta-analysis. Pedobiologia. 2016;59:215–23. https://doi.org/10.1016/j.pedobi.2016.04.001.
57. Gailis J, Turka I, Ausmane M. Soil tillage and crop rotation differently affect biodiversity and species assemblage of ground beetles inhabiting winter wheat fields. Agron Res. 2017;15:94–111.
58. Beillouin D, Ben-Ari T, Malézieux E, Seufert V, Makowski D. Positive but variable effects of crop diversification on biodiversity and ecosystem services. Glob Chang Biol. 2021;27:4697–710. https://doi.org/10.1111/gcb.15747.

59. Mäder P, Fliessbach A, Dubois D, Gunst L, Fried P, Niggli U. Soil fertility and biodiversity in organic farming. Science. 2002;296:1694–7. https://doi.org/10.1126/science.1071148.
60. Benton TG, Vickery JA, Wilson JD. Farmland biodiversity: is habitat heterogeneity the key? Trends Ecol. Evol. 2003;18:182–8. https://doi.org/10.1016/S0169-5347(03)00011-9.
61. Bengtsson J, Ahnström J, Weibull A-C. The effects of organic agriculture on biodiversity and abundance: a meta-analysis. J Appl Ecol. 2005;42:261–9. https://doi.org/10.1111/j.1365-2664.2005.01005.x.
62. Tuck SL, Winqvist C, Mota F, Ahnström J, Turnbull LA, Bengtsson J. Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. J Appl Ecol. 2014;51:746–55. https://doi.org/10.1111/1365-2664.12219.
63. Hodgson JA, Kunin WE, Tomas CD, Benton TG, Gabriel D. Comparing organic farming and land sparing: optimizing yield and butterfly populations at a landscape scale: organic farming and land sparing. Ecol Lett. 2010;13:1358–67. https://doi.org/10.1111/j.1461-0248.2010.01528.x.
64. Vickery JA, Tallowin JR, Feber RE, Asteraki EJ, Atkinson PW, Fuller RJ, et al. The management of lowland neutral grasslands in Britain: effects of agricultural practices on birds and their food resources. J Appl Ecol. 2001;38:647–64. https://doi.org/10.1046/j.1365-2664.2001.00626.x.
65. Herzon I, Raatikainen K, Wehn S, Rūsiņa S, Helm A, Cousins S, et al. Semi-natural habitats in boreal Europe: A rise of a social-ecological research agenda. Ecol Soc. 2021;26:13. https://doi.org/10.5751/ES-12313-260213.
66. Pärtel M, Bruun H, Sammul M. Biodiversity in temperate European grasslands: origin and conservation. In Grassland Science in Europe 10. 2005.
67. Murgueitio E, Calle Z, Uribe F, Calle A, Solorio B. Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. For Ecol Manage. 2011;261:1654–63. https://doi.org/10.1016/j.foreco.2010.09.027.
68. Liang M, Liang C, Hautier Y, Wilcox KR, Wang S. Grazing-induced biodiversity loss impairs grassland ecosystem stability at multiple scales. Ecol Lett. 2021;24:2054–64. https://doi.org/10.1111/ele.13826.
69. Filazzola A, Brown C, Dettlaff MA, Batbaatar A, Grenke J, Bao T, et al. The effects of livestock grazing on biodiversity are multi-trophic: a meta-analysis. Ecol Lett. 2020;23:1298–309. https://doi.org/10.1111/ele.13527.
70. Wang C, Tang Y. A global meta-analyses of the response of multi-taxa diversity to grazing intensity in grasslands. Environ Res Lett. 2019;14(11): 114003. https://doi.org/10.1088/1748-9326/ab4932.
71. van Klink R, Wallis DeVries MF. Risks and opportunities of trophic rewilding for arthropod communities. Philos Trans Roy Soc B Biol Sci. 2018;373:20170441. https://doi.org/10.1098/rstb.2017.0441.
72. de Leeuw J, Rizayeva A, Namazov E, Bayramov E, Marshall MT, Etzold J, et al. Application of the MODIS MOD 17 net primary production product in grassland carrying capacity assessment. Int J Appl Earth Obs Geoinf. 2019;78:66–76. https://doi.org/10.1016/j.jag.2018.09.014.
73. Santos FM, Gilberto T, Daniel PD, Chaer GM. Recovering ecosystem functions through the management of regenerating community in agroforestry and plantations with Khaya spp. in the Atlantic forest. Brazil For Ecol Manage. 2021;482:118854.
74. Ortiz I, Rey Benayas AJM, Cayuela L. Establishment and natural regeneration of native trees in agroforestry systems in the Paraguayan Atlantic forest. Forests. 2022;13:2045. https://doi.org/10.3390/f13122045.
75. Locqueville J, Labeyrie V, McKey D, Sanabria OL, Caillon S. Semi-domesticated crops have unique functional roles in agroecosystems: perennial beans (Phaseolus dumosus and P. coccineus) and landscape ethnoecology in the Colombian Andes. J Ethnobiol. 2022;42(2):198–216. https://doi.org/10.2993/0278-0771-42.2.198.
76. Faucon M, Houben PD, Lambers H. Plant functional traits: soil and ecosystem services. Trends Plant Sci. 2017;22:385–94.
77. Sandström C, Ring I, Olschewski R, Simoncini R, Albert C, Acar S, Adeishvili M, Allard C, Anker Y, Arlettaz R, Bela G, Coscieme L, Fischer A, Fürst C, Galil B, Hynes S, Kasymov U, Marta-Pedroso C, Mendes A, Molau U, Pergl J. Mainstreaming biodiversity and nature's contributions to people in Europe and Central Asia: insights from IPBES to inform the CBD post-2020 agenda. Ecosyst People. 2023;19:1.
78. Page C, Witt B. A leap of faith: regenerative agriculture as a contested worldview rather than as a practice change issue. Sustainability. 2022;14:14803.
79. Lal R, Reicosky DC, Hanson JD. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage Res. 2007;93(1):1–2.
80. Ebelhar SA, Frye WW, Blevins RL. Nitrogen from legume cover crops for no-tillage corn. Agron J. 1984;76(1):51–5.
81. Russelle MP, Entz MH, Franzluebbers AJ. Reconsidering integrated crop–livestock systems in North America. Agron J. 2007;99(2):325–34.
82. Zomer RJ, Bossio DA, Sommer R, Verchot LV. Global sequestration potential of increased organic carbon in cropland soils. Sci Rep. 2017;7:15554.
83. Dudek M, Rosa A. Regenerative agriculture as a sustainable system of food production: concepts, conditions, perceptions and initial implementations in Poland, Czechia and Slovakia. Sustainability. 2023. https://doi.org/10.3390/su152215721.
84. Elrick W, Luke H, Stimpson K. Exploring opportunities and constraints of a certification scheme for regenerative agricultural practice. Agroecol Sustain Food Syst. 2022;46(10):1527–49.
85. Day C, Cramer H. Transforming to a regenerative U.S. agriculture: the role of policy, process, and education. Sustain Sci. 2022;17:585–601.
86. Giller K, Hijbeek R, Andersson J, Sumberg J. Regenerative agriculture: an agronomic perspective. Outlook Agric. 2021;50:13–25.
87. McElwee P, Calvin K, Campbell D, Cherubini F, Grassi G, Korotkov V, Le Hoang A, Lwasa S, Nkem J, Nkonya E, Saigusa N, Soussana JF, Taboada MA, Manning F, Nampanzira D, Smith P. The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN sustainable development goals. Glob Chang Biol. 2020;26(9):4691–721. https://doi.org/10.1111/gcb.15219.
88. Adhikari B, Prescott GW, Urbach D, Chettri N, Fischer M. Nature's contributions to people and the Sustainable development goals in Nepal. Environ Res Lett. 2022;17:093007.
89. Pete S, Keesstra S. The role of soils in delivering Nature's Contributions to People *Phil*. Trans. 2021. https://doi.org/10.1098/rstb.2020.0169.
90. Smith P, Keesstra SD, Silver WL, et al. Soil-derived Nature's Contributions to People and their contribution to the UN Sustainable Development Goals. (2021). (2021). Philosophical Transactions of the Royal Society of London. Series B Biol Sci. 2021; 376(1834):20200185. https://doi.org/10.1098/rstb.2020.0185
91. de Medeiros EV, Notaro KDA, de Barros JA, Duda GP, Moraes MDCHDS, Ambrosio MMDQ, Negreiros AMP, Sales Júnior R. Soils from intercropped fields have a higher capacity to suppress black root rot in cassava, caused by Scytalidium lignicola. J Phytopathol. 2019;167:209–17.
92. Vukicevich E, Lowery T, Bowen P, Úrbez-Torres JR, Hart M. Cover crops to increase soil microbial diversity and mitigate decline in perennial agriculture: A review. Agron Sustain Dev. 2016; 36.
93. Lemaire G, Franzluebbers A, Carvalho PCDF, Dedieu B. Integrated crop-livestock systems: strategies to achieve synergy between agricultural production and environmental quality. Agr Ecosyst Environ. 2014;190:4–8.

94. Ma H, Zhou J, Ge J, Nie J, Zhao J, Xue Z, Hu Y, Yang Y, Peixoto L, Zang H, Zeng Z. Plant soil. 2022; 480, 71–84
95. Sun F, Pan K, Olatunji OA, Li Z, Chen W, Zhang A, Song D, Sun X, Huang D, Tan X. Specific legumes allay drought effects on soil microbial food web activities of the focal species in agroecosystem. Plant Soil. 2019;437:455–71.
96. Yang T, Siddique KHM, Liu K. Cropping systems in agriculture and their impact on soil health—a review. Global Ecol Conserv. 2020;23: e01118. https://doi.org/10.1016/j.gecco.2020.e01118.
97. Barbieri P, Dumont B, Benoit M, Nesme T. Opinion paper: livestock is at the heart of interacting levers to reduce feed-food competition in agroecological food systems. Animal. 2022;16: 100436. https://doi.org/10.1016/j.animal.2021.100436.
98. Lupwayi NZ, Larney FJ, Blackshaw RE, Pearson DC, Eastman AH. Soil microbial biomass and its relationship with yields of irrigated wheat under long-term conservation management. Soil Sci. 2018;183:179–87.
99. Ingels CA, Scow KM, Whisson DA, Drenovsky RE. Effects of cover crops on grapevines, yield, juice composition, soil microbial ecology, and gopher activity. Am J Enol Vitic. 2005;56:19–29.
100. Whitelaw-Weckert MA, Rahman L, Hutton RJ, Coombes N. Permanent swards increase soil microbial counts in two Australian vineyards. Appl Soil Ecol. 2007;36:224–32. https://doi.org/10.1016/j.apsoil.2007.03.003.
101. Steenwerth K, Belina KM. Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem. Appl Soil Ecol. 2008;40:359–69. https://doi.org/10.1016/j.apsoil.2008.06.006.
102. Eric Vukicevich D. Thomas Lowery, Jonathan A. Bennett and Miranda Hart.2019. Influence of Groundcover Vegetation, Soil Physicochemical Properties, and Irrigation Practices on Soil Fungi in Semi-arid Vineyards. Frontiers in Ecology and Evolution | www.frontiersin.org 1 April 2019 | Volume 7 | Article 118.
103. McGuire A. Regenerative Agriculture: Solid Principles, Extraordinary Claims. 2018. http://csanr.wsu.edu/regen-ag-solid-principles-extraordinary-claims/ Accessed: 01 Feb 2021.
104. Burgess PJ, Harris J, Graves AR, et al. Regenerative agriculture: identifying the impact; enabling the potential. Report for SYSTEMIQ. Cranfield: Cranfield University; 2019.
105. Merfield CN. An analysis and overview of regenerative agriculture. Report number 2–2019. Lincoln: The BHU Future Farming Centre; 2019.
106. Herzon I, Raatikainen K, Wehn S, Rūsiņa S, Helm A, Cousins S, et al. Semi-natural habitats in boreal Europe: a rise of a social-ecological research agenda. Ecol Soc. 2021;26:13. https://doi.org/10.5751/ES-12313-260213.
107. Intergovernmental Panel on Climate Change (IPCC). Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. 2019.
108. Rotz CA, Asem-Hiablie S, Place S, Thoma G. Environmental footprints of beef cattle production in the United States. Agric Syst. 2019;169:1–13. https://doi.org/10.1016/j.agsy.2018.11.005.
109. Herrero M, et al. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc Natl Acad Sci. 2013;110:20888–93. https://doi.org/10.1073/pnas.1308149110.
110. Dudley QM, Liska AJ, Watson AK, Erickson GE. Uncertainties in life cycle greenhouse gas emissions from U.S. beef cattle. J Clean Prod. 2014;75:31–9. https://doi.org/10.1016/j.jclepro.2014.03.087.
111. Badgery WB, Simmons AT, Murphy BW, Rawson A, Andersson KO, Lonergan VE. The influence of land use and management on soil carbon levels for crop-pasture systems in Central New South Wales. Australia Agric Ecosyst Environ. 2014;196:147–57. https://doi.org/10.1016/j.agee.2014.06.026.
112. Lewis DJ, Lennox M, O'Geen A, Creque J, Eviner V, Larson S, Harper J, Doran M, Tate KW. Creek carbon: mitigating greenhouse gas emissions through riparian restoration. Novato: University of California Cooperative Extension in Marin County; 2015.
113. Machmuller MB, Kramer MG, Cyle TK, Hill N, Hancock D, Thompson A. Emerging land use practices rapidly increase soil organic matter. Nat Commun. 2015;6:6995. https://doi.org/10.1038/ncomms7995.
114. Stanley PL, Rowntree JE, Beede DK, DeLonge MS, Hamm MW. Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA beef finishing systems. Agric Syst. 2018;162:249–58. https://doi.org/10.1016/j.agsy.2018.02.003.
115. Earl JM, Jones CE. The need for a new approach to grazing management—is cell grazing the answer? Rangel J. 1996;18:327. https://doi.org/10.1071/RJ9960327.
116. Strohm H, Watt KA. Native perennial grasses continue expanding across TomKat ranch. TomKat ranch educational foundation. 2019. https://tomkatranch.org/2019/04/24/native-perennialgrassescontinue-expanding-across-tomkat-ranch/.
117. Teague WR, Dowhower SL, Baker SA, Haile N, DeLaune PB, Conover DM. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tallgrass prairie. Agric Ecosyst Environ. 2011;141:310–22. https://doi.org/10.1016/j.agee.2011.03.009.
118. Ryals R, Kaiser M, Torn MS, Berhe AA, Silver WL. Impacts of organic matter amendments on carbon and nitrogen dynamics in grassland soils. Soil Biol Biochem. 2014;68:52–61. https://doi.org/10.1016/j.soilbio.2013.09.011.
119. Millar GD, Badgery WB. Pasture cropping: a new approach to integrate crop and livestock farming systems. Animal Production Science. 2009;2009(49):777–87.
120. Dudek M, Rosa A. Regenerative agriculture as a sustainable system of food production: concepts, conditions perceptions and initial implementations in Poland Czechia and Slovakia. Sustainability. 2023. https://doi.org/10.3390/su152215721.
121. Ittonell P, Mujtar V, Félix G, Kebede Y, Laborda L, Soto R, Vente J. Regenerative agriculture—agroecology without politics. Front Sustain Food Syst. 2022. https://doi.org/10.3389/fsufs.2022.844261.