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Review

Regenerative Agriculture: Insights and Challenges in Farmer Adoption

Cristiano Moisés [1,2], Margarida Arrobas [1,2], Dimitrios Tsitos [3], Diogo Pinho [4], Raiza Figueiredo Rezende [5] and Manuel Ângelo Rodrigues [1,2,*]

[1] Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal; cristiano.moises@ipb.pt (C.M.); marrobas@ipb.pt (M.A.)
[2] Laboratório para a Sustentabilidade e Tecnologia em Regiões de Montanha, Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal
[3] AgroSystemic SA, Rue des Eaux-Vives 23, c/o Fidaction Fisc-Compta SA, 1207 Geneva, Switzerland; dimitri@agrosystemic.com
[4] Monte Silveira Farm, Rua Diogo da Fonseca, 7, R/C esquerdo, 6000-184 Castelo Branco, Portugal; diogo.pinho@montesilveira.com
[5] CHYPRA—Associação Pro Saúde e Agricultura Regenerativa, 191 Rua Ferreira Borges, 2º Esq., 1350-132 Lisboa, Portugal; raiza@agrosystemic.com
* Correspondence: angelor@ipb.pt

Abstract

Regenerative agriculture has emerged as a new organic farming movement, initially difficult to distinguish from similar approaches. Its core concerns, such as ecosystem degradation caused by intensive farming, align with those of many other organic systems. However, regenerative agriculture prioritizes soil health, biodiversity, and social equity, setting itself apart through its scalability and flexibility. Unlike other ecological farming methods, often limited to smaller scales, regenerative agriculture aims to be implemented on large farms, typically major contributors to pollution due to reliance on external inputs like fertilizers and pesticides. Notably, regenerative certification standards are more flexible, allowing the use of industrially synthesized inputs under specific conditions, provided that regenerative principles are upheld. This review systematically examines seven core regenerative practices: no-tillage farming, crop rotation, cover cropping, green manures, intercropping, perennial cover systems, and integrated crop-livestock systems. It outlines the practical advantages and ecological benefits of each, while identifying key adoption challenges, including costs, farm size, and institutional barriers. The paper argues that addressing these issues, particularly concerning scale and socio-economic constraints, is essential for broader adoption. By synthesizing recent evidence, this review clarifies the distinctiveness of regenerative agriculture and highlights pathways for its scalable implementation.

Keywords: soil health; conservation agriculture; crop rotation; cover crops; intercropping; integrated crop-livestock

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1. Introduction

Food production, both in terms of quantity and quality, represents an ongoing challenge for contemporary societies. The global population is projected to continue growing, with the most reliable estimates predicting an increase over the next 50 to 60 years, reaching a peak of approximately 10.3 billion by the mid-2080s, up from 8.2 billion in 2024 [1]. However, this growth cannot justify expanding agricultural activities into new territories, especially those that are unique ecosystems that must be preserved [2,3]. Consequently, productivity levels on currently used agricultural lands must not decline; rather, they may need to increase to meet the food requirements of a growing population. This will not be achievable if soil degradation and loss of fertility continue. Furthermore, the ongoing contamination of water resources due to agricultural nitrate leaching must be addressed [4], as well as the contribution of agricultural practices to greenhouse gas emissions, which remain unacceptable [5].

The intensification of agriculture, driven by biotechnology, including developing improved crop varieties, genetically modified organisms, new plant protection products, and the widespread use of mineral fertilizers, has enabled large-scale food production [6]. The persistence of hunger worldwide is believed to be more closely related to the distribution and access to food for vulnerable populations rather than the capacity of agricultural ecosystems to produce food in sufficient quantities [7]. Food waste, particularly in certain societies in the Global North, also exacerbates the issue [8].

Intensive or conventional farming practices tend to leave a significant ecological footprint. These practices lead to a marked reduction in biodiversity, primarily through the establishment of monocultures, the cultivation of a limited number of varieties within each species, and the use of herbicides that reduce plant biodiversity in agricultural fields [9]. This issue is exacerbated by the extensive use of broad-spectrum insecticides and fungicides, which harm non-target organisms, disrupt ecosystems, and create conditions where farming practices become increasingly dependent on such chemicals, thereby diminishing the resilience of agroecosystems [10].

The effects of intensive agriculture on aquifers, watercourses, and oceans are equally concerning. The most notable issue is the contamination of water by agricultural nitrates, which is considered a primary contributor to eutrophication [11]. When nitrogen fertilizers are applied in large quantities, nitrates are the form that stabilizes in the soil. Being highly soluble in water, nitrates are leached during significant precipitation events, reaching watercourses and causing ecological imbalances due to the excessive growth of aquatic plants. As this biomass decays, oxygen depletion in aquatic ecosystems can occur, leading to the mortality of aerobic organisms [11,12]. Agricultural ecosystems also release substantial amounts of phosphorus, mainly when excessive quantities of animal manure are applied [13], along with dissolved organic carbon and dissolved organic nitrogen, resulting in severe contamination of aquatic ecosystems [4].

Agricultural activity is a significant emitter of greenhouse gases. On one hand, it is important to consider the upstream activities that are highly energy-intensive, such as the production of machinery, agricultural equipment, and production inputs, all of which involve energy consumption and carbon dioxide emissions into the atmosphere [14]. There is also the issue of greenhouse gas emissions, particularly from intensive agriculture, notably nitrogen oxides, which result from the denitrification of excess nitrates in the soil and water [5,14]. Livestock production also contributes to atmospheric emissions, including enteric methane [15] and methane and ammonia primarily associated with manure management [16].

Soil degradation primarily occurs due to erosion, often exacerbated by excessive tillage or residual herbicides, leaving the soil bare for extended periods and making it vulnerable to precipitation and/or wind. Erosion is one of the leading environmental issues in some regions of the world (Figure 1), leading to the actual loss of soil and a reduction in the sustainability of the production system [17,18]. Additionally, secondary salinization, which can be human-induced through inorganic fertilizers and irrigation in arid and semi-arid regions where excess salts are not leached by rainfall during the wet season, is a significant form of soil degradation [19]. Soil acidification can also be exacerbated by agricultural practices, as plants tend to export more cations than anions [20,21], as well as using certain fertilizers with an acidifying effect, such as ammoniacal fertilizers and urea [21]. Soil compaction, another form of degradation, results from the passage of heavy machinery, which impairs soil drainage and aeration [22].

Figure 1. Different soil management approaches: conventional tillage (**left**) versus cover cropping with self-reseeding annual legume species (**right**) in olive orchards. Images illustrate soil erosion vulnerability under tillage (**left**) and the protective role of vegetative cover (**right**).

Organic farming systems aim to develop ways to feed humanity more sustainably. They seek to reduce energy consumption and minimize negative environmental impacts. These systems challenge traditional tillage practices and promote direct seeding. They recommend establishing evergreen systems to prevent bare soil, which can be achieved either through winter cover crops in arable farming or by maintaining diverse vegetation in the inter-row spaces of fruit orchards. Organic farming also advocates for crop rotation and the use of green manures. These practices reduce the risk of erosion and increase the organic matter content of the soil, which is essential for its fertility. Furthermore, organic farming aims to improve the quality of agricultural products by reducing the risk of contamination from pesticide residues and producing more nutritious and healthier food [23,24]. Additionally, organic farming aims to improve the well-being of farmers. Both income and social welfare are critical aspects of the sustainability of agricultural activities [25,26]. The abandonment of farming and the search for employment in urban areas are contributing to significant social issues in rural and urban regions worldwide [27,28].

Among the emerging approaches within organic agriculture, regenerative farming offers a holistic and scalable pathway that integrates environmental, economic, and social goals [26,29–33]. This review aims to provide a practice-based assessment of regenerative agriculture by analyzing seven key techniques frequently cited in the literature and adopted by practitioners: no-tillage, crop rotation, winter cover crops, green manures, intercropping, cover cropping in perennial systems, and integrated crop-livestock systems. The paper also identifies and discusses barriers to adoption, such as high equipment costs, lack of technical knowledge, policy constraints, and socio-economic challenges, especially in the context of farm scale. While the emphasis is on global applicability, particular attention is given to how these practices perform and are adopted across different farm sizes. By connecting the principles of regenerative agriculture with real-world implementation challenges, this review contributes to a clearer understanding of what makes this system distinct and how it may be scaled.

2. Stabilization of the Concept and Practices of Regenerative Agriculture

Although the term "regenerative agriculture" is not a recent concept, having been first introduced by Francis et al. [34], according to an in-depth review of the literature conducted by other scholars [30,35], it has recently emerged as a relatively well-defined system, distinct from other organic agriculture movements. In its contemporary context, the concept of regenerative agriculture was introduced by Dr. George Washington Carver and later popularized by Robert Rodale of the Rodale Institute. Robert Rodale coined the term "regenerative organic" to differentiate a farming model that goes beyond mere sustainability [36].

According to this perspective, the fundamental distinction between the primary movements of organic agriculture and regenerative agriculture lies in their respective focuses. The former centers on maintaining the current state, aiming for sustainability by preserving agricultural productivity and other non-productive functions of the cropping system for future generations. In contrast, regenerative agriculture recognizes that intensive farming practices have contributed to the degradation of agricultural lands (e.g., erosion, reduced organic carbon content in soils, compaction, decreased water retention, etc.) and advocates for measures to improve these conditions. This focus on restoration is perhaps the defining characteristic of regenerative agriculture, which aligns with the "regeneration" concept, where simple maintenance is deemed inadequate. Regenerative practices are expected to enhance soil health, which serves as the foundational basis for agricultural productivity [26,29,37,38].

Farmers who adopt regenerative agricultural practices can obtain certification for their production methods. The Regenerative Organic Certified® standard was established in 2017 by a coalition of farmers, business leaders, and experts in soil health, animal welfare, and social fairness, collectively known as the Regenerative Organic Alliance [39]. This alliance was founded by the Rodale Institute, Dr. Bronner's, and Patagonia. The regenerative organic certification builds upon the USDA-certified organic framework. It uses it as a baseline while adding critical criteria and benchmarks integrating the three key pillars of regenerative organic agriculture: soil health, animal welfare, and social fairness [36]. As a result, Regenerative Organic Certified® is regarded as a revolutionary new certification for food, fiber, and personal care ingredients, representing the highest global standard for organic agriculture [36]. This certification can be implemented by various local certifying entities, many of which also certify other production methods (e.g., ECOCERT, CERTIS, etc.). Opportunities are also being created to develop various regenerative certification schemes, to increase the number of farmers and ranchers who can become certified [40]. Currently, 19,468,390 acres and 379 farms and ranches have been certified (https://regenorganic.org/, accessed on 24 July 2025). Despite this progress, barriers such as high equipment cost, variability in crop income, and competition for water resources persist. Studies in North America and Europe have highlighted that knowledge transfer and financial incentives are crucial in overcoming these hurdles [26,28,40].

The principles of regenerative agriculture can be summarized as follows: minimizing soil disturbance; minimizing the use of chemical inputs; maximizing biodiversity, both animals and plants; keeping the soil covered with crops as long as possible; and adapting to the local environment [36]. Essentially, it focuses on the significant environmental issues that intensive conventional agriculture can cause and advocates for practices that reduce environmental impacts while improving the capacity of agroecosystems to produce food in both quantity and quality for a growing global population [30,31,41].

Most regenerative agricultural practices focus on increasing soil organic carbon based on the premise that this enhances crop productivity and mitigates climate change [30]. These practices promote the accumulation of carbon in the soil, primarily derived from plant roots and mycorrhizal fungi, thereby boosting soil biodiversity. The activity of mycorrhizal fungi, along with symbiotic nitrogen fixation, reduces the need for phosphate and nitrogen fertilizers [38,42]. Increased earthworms and mycorrhizal fungi help regenerate soil structure, improving its ability to sequester carbon [43]. These changes will bring broader environmental benefits, including climate change mitigation, enhanced water quality, and improved functional biodiversity [31]. Additionally, there are potential economic and human health benefits through improved crop yields and nutritional quality [24,44].

Many farming practices currently advocated by regenerative agriculture have been extensively studied by the scientific community for a long time, often without explicit reference to this specific agricultural system. A significant body of theoretical literature highlights the benefits of practices such as crop rotation, no-till farming, cover cropping, green manuring, integrated pest management, and mixed farming systems, frequently without positioning them within any organic farming movement. These studies have generally focused on emphasizing the environmental benefits of these practices, as well as the potential economic returns, intending to identify more effective pathways for producers. Thus, regenerative agriculture can be seen as a compilation of best practices centered on soil health while also addressing the mitigation of environmental challenges and the socio-economic improvement of stakeholders, which have been developed and refined over recent decades.

In contrast to many organic and agroecological systems that strictly prohibit synthetic inputs, regenerative agriculture permits their conditional use, for instance, applying mineral nitrogen fertilizers when organic sources are unavailable, or targeted use of herbicides during transition periods to establish cover crops. These flexibilities are designed to support large-scale operations where abrupt elimination of conventional inputs could threaten yield stability or economic viability. Another key distinction lies in the certification structure: unlike traditional organic certification, which focuses predominantly on input structure, regenerative certification frameworks integrate quantifiable benchmarks for soil carbon sequestration, biodiversity, and labor rights, enabling a more multidimensional assessment of sustainability. These elements make regenerative agriculture not only an environmental model but also a socio-economic one, emphasizing farmer livelihoods alongside ecosystem health.

3. Most Relevant Practices of Regenerative Agriculture

Some of the most common regenerative agriculture methods include no-till systems, cover cropping, crop rotations, and integrated crop-livestock systems, all of which contribute to improving soil health, enhancing biodiversity, and minimizing the use of chemical inputs [36]. In alignment with the principles of regenerative agriculture, this document presents a review of practices organized into seven key topics, as they frequently appear in the titles or keywords of specialized literature. These topics are no-tillage, crop rotation, winter cover crops, green manures, intercropping, cover cropping in perennial systems, and integrated crop-livestock systems.

Despite their proven environmental benefits, the adoption of regenerative agriculture practices faces considerable context-specific barriers. For instance, while no-tillage techniques enhance soil structure and carbon retention, they require access to specialized equipment often unaffordable for smallholder farmers. Similarly, integrated crop-livestock systems demand significant land planning and labor availability, making them more viable on mid- to large-scale farms. Intercropping, although effective in nutrient cycling, may increase labor demands and require new knowledge, especially where extension services are lacking. These and several other aspects related to the adoption of regenerative agriculture are summarized in Table 1 and discussed in the next sections.

Table 1. Summary of the main environmental, ecological, social, and technical benefits and constraints, and the applicability of the seven agroecological practices developed in this study.

Agricultural Practices	Key Benefits	Environmental Issues	Economic/Social Constraints	Technical Constraints	Applicability
No-tillage	Soil conservation; Carbon sequestration; Soil health; Energy saving	Non-selective herbicide reliance	Reduced costs	High-cost equipment	Large farms
Crop rotation	Soil health; Biodiversity; Less nutrient mining	No	No equivalent income crops	Diverse specialized equipment	All farm sizes
Winter cover crops	Soil conservation; Lower nitrate leaching	No	Seeding cost	No	All farm sizes
Green manures	Soil fertility; More N available if legumes	Nitrate leaching risk if legumes	Seeding cost	No	All farm sizes
Intercropping	Biodiversity; Higher income	No	Labor availability	Mechanization difficult	Small family farms
Cover cropping in perennials	Soil conservation; Carbon sequestration; Soil health; Biodiversity	No	Water competition and yield loss	High costs: Seeds, seeding and cover crop management	All farm sizes
Crop-livestock systems	Soil conservation; Carbon sequestration; Soil health; Biodiversity	No	Extra income from animal products	Labor, fencing, crop damage, supplemental feed	Mid and large farms

3.1. No-Tillage

Soil non-tillage or reduced tillage practices have been the subject of extensive research, particularly since the 1960s. The terms used to describe these practices are varied, as are the methods for their implementation. Under the broad umbrella of conservation agriculture, terms are used to describe sowing processes that involve placing seeds into the soil without prior tillage to create a seedbed, such as no-tillage, direct seeding, or direct drilling [2,45]. Practices are also considered part of conservation agriculture when soil disturbance occurs only on part of the surface, with the remaining area, typically no less than 30%, left covered with residues from the previous crop. In such cases, terms like minimum or ridge tillage may be used [2,45]. Regenerative agriculture has increasingly emphasized practices commonly associated with conservation agriculture [30], as minimizing or entirely avoiding soil tillage can improve soil quality, reversing the detrimental effects of decades of continuous soil disturbance. This is particularly evident when moldboard plows are employed, as they invert the topsoil layers [46,47].

Although most research has focused on improving soil fertility by implementing conservation agriculture practices, these techniques were initially promoted in regions characterized by significant large-scale grain production and considerable water and/or wind erosion risks. As a result, countries such as the United States, Canada, Brazil, Argentina, Paraguay, and Australia have been among the early adopters of conservation agriculture on a larger scale [2,48]. In Brazil, for instance, it is estimated that over 60% of the country's total agricultural land is cultivated using no-tillage systems [45].

Maintaining soil cover with vegetation is an effective strategy to reduce soil erosion. Plant roots anchor the soil, while surface vegetation helps mitigate soil disaggregation caused by the direct impact of raindrops and decreases surface runoff, thereby enhancing water infiltration [6]. In addition to controlling erosion, minimizing or reducing soil tillage limits the excessive exposure of the stabilized organic material in the soil to heterotrophic microorganisms, which thrive due to increased oxygen availability and the degradation of clay-humic complexes. This leads to more extensive mineralization of organic matter and a subsequent reduction in soil biodiversity [6]. It is well-established that conservation agriculture practices contribute to increasing soil organic matter content [46,47]. Furthermore, the growing imperative to address global warming, including strategies such as soil carbon sequestration, has underscored the significance of conservation agriculture practices [30,49].

Conservation agriculture offers several advantages, primarily through reductions in fuel costs and labor time [46,48]. However, there are notable disadvantages, which may explain why not all farmers have adopted these practices. The potential for reduced productivity and the requirement for specialized equipment, particularly a significant consideration for farms with limited acreage, are likely the major limitations [46,48]. Additionally, the need for herbicides to protect young seedlings from competition with weeds, often associated with the use of genetically modified crops, represents a negative aspect, especially for farmers seeking to implement organic farming systems [50,51]. Consequently, while no-tillage systems may be readily adopted in regions characterized by large-scale grain production, progress in areas with smallholdings or farms composed of numerous small plots is less likely in terms of adopting these non-tillage practices.

3.2. Crop Rotation

Crop rotation is a cornerstone practice within organic farming movements, including regenerative agriculture. This technique can enhance soil fertility and reduce the prevalence of pests, diseases, and weeds, all contributing to decreased reliance on external production inputs [52,53].

From an experimental standpoint, the benefits of crop rotation were demonstrated through the four-year Norfolk rotation system developed in 18th-century England [54]. The principle of crop rotation involves dividing the agricultural area into a number of plots corresponding to the number of years in the rotation cycle. In the first year, each crop in the rotation is planted in one of the plots, and a systematic, sequential rotation of different crops occurs across the plots. After completing the full rotation cycle, each crop returns to its original plot [52].

The benefits of crop rotation are numerous and multifaceted. Each crop typically hosts specific pests and diseases that tend not to affect crops from different botanical groups. After one year of cultivation, the dormant forms of pests and diseases remain in the cultivated plots or surrounding areas, compromising the phytosanitary conditions of the crop in the subsequent year. By rotating crops, these pests and diseases are deprived of the necessary food sources for their development and reproduction, thus significantly reducing their potential for proliferation [55,56]. Regarding weeds, it is essential to incorporate crop species with varying growth cycles into the rotation, some for the autumn–winter season and others for the spring–summer season. This disrupts the biological cycles of weeds through different soil preparation and harvest dates while also helping to prevent resistance to herbicide use [52,56].

Crop rotation also provides significant benefits to soil fertility. By incorporating crops with distinct nutritional requirements that extract nutrients from different soil depths, the intensity of nutrient mining is reduced, which enhances the soil's ability to naturally replenish nutrients in the soil solution through biogeochemical processes [57,58]. Moreover, legumes play a crucial role in this process due to their ability to form symbiotic relationships with nitrogen-fixing microorganisms, thereby enhancing nitrogen availability within the system [42]. Certain legumes develop proteoid roots in phosphorus-deficient soils and secrete organic compounds into the soil, allowing them to access phosphorus that is otherwise unavailable to other species [59,60]. Once in the soil, legume residues can undergo mineralization through the action of phosphatases, releasing phosphorus for subsequent crops in the rotation [60,61]. Furthermore, the implementation of crop rotation fosters the retention of larger quantities of crop residues in the soil, which enhances nutrient cycling, boosts organic matter content, and stimulates biological activity within the soil [62,63].

An important aspect is why most farmers do not adopt crop rotation despite the numerous potential benefits. In a given socio-economic context, it is often unlikely that farmers can identify a sufficient number of crops with equivalent income potential [64,65]. Incorporating low-yield crops into the rotation typically results in a short-term decrease in profitability, which may be unsustainable for the farm family. Furthermore, a greater variety of crops usually necessitates specialized machinery with low annual utilization rates and high depreciation costs. Additionally, farmers must invest more time and resources in monitoring market trends and managing the specific cultivation requirements of different crops. Nevertheless, regenerative agriculture must continue to advocate for crop rotation, as it remains one of the most effective strategies to reduce dependence on external production inputs and improve soil fertility. While the economic benefits may only become apparent in the medium to long term, the ecological advantages are significant and long-lasting [57,58].

3.3. Winter Cover Crops

The term "winter cover crops" denotes a function distinct from providing food or feed, although it may occasionally serve these roles. In temperate regions, these crops typically occupy the soil during the autumn and winter months, following the cultivation of a main crop in the spring and summer. Cover crops are primarily associated with environmental protection, and alongside the main crop, they contribute to what are sometimes called "evergreen systems."

A frequently assigned role of winter cover crops is soil protection from erosion [66]. These crops are generally sown at the end of the summer and establish during the autumn and winter months. In the following spring, they are typically incorporated into the soil before planting the main crop. Beyond mitigating erosion, winter cover crops can enhance soil physical properties, including porosity and bulk density [67], and increase soil organic matter and nutrient cycling [68,69].

Given the impact of intensive agriculture on nitrate leaching into watercourses and the denitrification process, which results in the emission of nitrogen oxides into the atmosphere, much of the research on winter cover crops has focused on their role in absorbing excess nitrogen applied to the summer crop, which may be lost from the soil once autumn rainfall begins. In this context, these crops are often called catch crops [64,70]. These crops are established after the main crop has grown, absorbing the residual inorganic nitrogen in the soil and retaining it within the system as organic nitrogen. This organic nitrogen is returned to the soil in the following spring when the main crop is sown.

Cover crops can also be sown with the specific aim of enhancing soil health. Some of the most commonly used cover crops belong to the Brassicaceae family, and these have been shown to exert a fumigant effect on nematodes and other soilborne pathogens, thereby reducing the risk of root damage [71]. Crimson clover (*Trifolium incarnatum*) has also proven effective in suppressing diseases caused by *Phytophthora nicotianae*, *Phytopythium vexans*, and *Rhizoctonia solani* [72]. Additionally, the sowing of winter cover crops has been employed to control certain weed species [73].

Regenerative agriculture acknowledges the benefits for both soil health and the environment and has actively promoted the integration of cover crops, in a broad sense, into agroecosystems, making it a key area for intervention [38,74]. Generally, significant challenges are not expected in adopting cover crops within agricultural systems. However, in herbaceous horticulture, it is common to grow cash crops during the winter, which leads to competition for space and time with the main crop.

3.4. Green Manures

The cultivation of plants as green manure is an ancient practice aimed at enhancing soil fertility, widely endorsed in all organic farming systems and particularly emphasized in regenerative agriculture [38,75,76]. The concept inherently suggests that these plants are not cultivated as cash crops but incorporated into the soil to improve fertility [77]. Although this concept may appear similar to winter cover crops, it has emerged in the international literature with a somewhat distinct interpretation. While winter cover crops and catch crops are more strongly associated with environmental protection, green manures are more closely related to enhancing soil fertility.

Although many species have been used as green manures [75,76], the focus has primarily been on legumes, given their ability to access atmospheric nitrogen [75,78]. Most legumes form symbiotic relationships with microorganisms from the Rhizobiaceae family, commonly known as rhizobia. These microorganisms can break the triple covalent bond between the nitrogen atoms in the N_2 molecule, thereby converting atmospheric nitrogen into forms that can be utilized to synthesize amino acids and other nitrogenous compounds [42]. When "green manure" is used without referring to legume cultivation, it becomes more aligned with the broader concept of cover crops.

When cultivated as green manures, legumes are typically incorporated into the soil. Their nitrogen-rich tissues, which have a low carbon/nitrogen ratio, mineralize rapidly, releasing nitrogen for the subsequent crop in the rotation [75,79]. Alternatively, the aboveground biomass can be left on the soil as mulch, offering additional benefits such as soil protection against erosion and a reduction in temperature and moisture loss [33,80]. However, concerns have been raised regarding the potential nitrogen loss to the atmosphere through ammonia volatilization [81].

On the other hand, regardless of whether the green manure is a legume, contains legumes, or consists of other botanical species, the substantial amount of plant debris incorporated into the soil can produce a multifunctional effect on soil health. This includes increasing organic matter content [76], enhancing phosphorus availability [53,59], and generating various beneficial effects on soil microbiology [75].

3.5. Intercropping

Intercropping different species is an ancient practice that has endured through the ages. While there are various approaches to establishing crop mixtures, the term "intercropping" will be used in this review to refer to the cultivation of two or more species that overlap partially or fully in both space and time.

The principles of intercropping are founded on the premise, substantiated by experimental evidence, that cultivating two or more crop species simultaneously within the same field enhances overall productivity compared to growing each species individually over an equivalent area. The interactions among different species can result in complementarity, cooperation, compensation, and/or competition [82]. Successful species mixtures that yield positive intercropping outcomes exhibit minimal competitive interference, thereby underscoring the advantages of complementarity, cooperation, and compensation [82]. Furthermore, competition within intercropping systems is often assessed using well-established indicators, the most widely recognized being the land equivalent ratio (LER). LER quantifies the relative land area required for monocultures to achieve the same yields as intercropped systems [83] and has been extensively utilized in empirical research, offering critical insights for optimizing intercrop management strategies [84,85].

Although intercropping is practiced globally, it has predominantly persisted in less developed regions [84,85]. In countries with more advanced agricultural systems, full mechanization of farming operations has rendered traditional intercropping systems less viable or even impractical, particularly due to the manual labor required for tasks such as harvesting. Nevertheless, species mixtures remain prevalent in producing hay and other forages for animal feed, where intercropping continues to offer agronomic and economic benefits [86,87].

Although intercropping systems are advocated within the regenerative agriculture framework [38,88], their widespread adoption in large-scale grain production remains constrained by the challenges associated with mechanizing agronomic operations. Practices that demand increased labor input are often deemed impractical, despite the argument that they contribute to employment generation, an aspect of relevance given the ongoing rural-to-urban migration trends [27,28].

3.6. Cover Cropping in Perennial Woody Crops

Soil management in perennial woody crops has been a subject of extensive research. Historically, tillage was the predominant method for weed control; however, over time, management practices transitioned first to the application of herbicides and later to an integrated approach combining herbicide use along crop rows with the maintenance of spontaneous vegetation in the inter-rows. More recently, the practice of sowing cover crops in inter-row spaces has become increasingly common, serving multiple agronomic and ecological objectives. When vegetative cover is established either across the entire soil surface or specifically in the inter-rows, the term "cover cropping" is widely used [18,89].

One of the primary objectives of cover cropping is erosion control, particularly in regions where orchards and vineyards are cultivated on sloped terrain, as is common in the Mediterranean. The presence of permanent vegetation, even if it becomes senescent during the summer months, effectively mitigates soil loss caused by erosion [17,18].

Enhancing soil organic matter is an equally critical objective, particularly given that these traditionally tilled soils often exhibit low organic matter content [18,90]. Moreover, such soils have been recognized as potential carbon sequestration sites, which has further contributed to the promotion of cover cropping due to the diverse ecosystem services it provides [91,92].

Cover cropping with spontaneous vegetation is sometimes encouraged for its role in promoting biodiversity, while sown vegetation offers a range of targeted benefits. Specifically, sown cover crops can be selected to attract beneficial insects or pollinators [93] or to enhance soil properties [18,90]. Among the most widely promoted cover crops are legumes, primarily due to their nitrogen-fixing ability, which supports crop production without the reliance on synthetic nitrogen fertilizers, an important advantage for organic farming systems [77,81]. This vegetation type may constitute one of the key strategies for transforming agricultural systems previously classified as intensive, characterized by a heavy reliance on synthetic fertilizers and pesticides, into regenerative agriculture systems. These regenerative approaches aim to maintain productivity levels while significantly reducing the dependence on external inputs with high environmental impact.

Regenerative agriculture also emphasizes integrating vegetation within orchards to enhance soil health and functional biodiversity [30,38]. In some cases, buffer strips are established along the planting rows to provide refuge for beneficial organisms and act as biodiversity reservoirs [94]. This integration can also include mid-field woodlots, small, irregular patches of trees located within the agricultural matrix, which contribute to increased structural complexity and provide habitats for a wide range of species, further enhancing ecological balance and landscape connectivity [95,96]. Additional standard practices include planting rows of trees and/or shrubs to create alleys where agricultural, horticultural, or forage crops can be cultivated [97]. These diversified systems not only improve microclimatic conditions and reduce erosion but also facilitate natural pest control and nutrient cycling. In contrast to traditional cover cropping, which primarily focuses on supporting fruit trees and improving soil fertility, these systems pursue double cropping, aiming to generate additional profit from the crops produced in these alleys [97]. Moreover, the integration of multifunctional vegetation contributes to greater resilience against climatic stress and promotes a more balanced agroecosystem.

Although experimental studies have highlighted numerous benefits of cover cropping in perennial woody crops, many farmers in extensive regions worldwide continue to rely on tillage or herbicide applications [89,98]. In arid and semi-arid regions, such as southern Europe, where large rainfed olive groves and vineyards are prevalent, herbaceous vegetation can compete for water, a scarce and primary limiting factor for productivity in these agroecosystems. Several studies have reported a decline in productivity when highly expansive cover crops are used, although concurrent improvements in soil fertility are often observed [81,85,99]. For regenerative agricultural practices to be effectively adopted in these agroecosystems, it may be necessary to adjust the choice of vegetation to local agroecological conditions. For example, early maturing species or cultivars that enhance soil protection and fertility during the winter but die early in the spring could be employed to mitigate water competition [89,100].

Another important consideration is the management of cover crops. In theory, cover crops can be mowed and incorporated into the soil. However, this approach is not recommended in orchards due to the detrimental effects of soil tillage on tree roots and its potential to exacerbate erosion and promote organic matter mineralization. Alternatively, cover crops can be cut and left on the soil surface as mulch, which helps protect the soil from erosion and reduces soil temperature, thereby decreasing water loss through evaporation [101]. However, if the cover crops are legume-rich, nitrogen losses may occur, likely due to ammonia volatilization [81]. In regions where livestock integration is feasible, cover crop management can be achieved through grazing, which benefits animal nutrition while reducing competition between herbaceous vegetation and trees [85]. Nevertheless, combining fruit production with livestock farming may also present challenges, as discussed in Section 3.7.

3.7. Integrated Crop–Livestock Systems

In the relatively recent past, agriculture and livestock farming were closely intertwined, as animals provided the primary source of draft power on farms. The number of working animals was proportional to the size of the agricultural operation, and livestock breeding played a crucial role in replacing aging animals or supplying animals for the market, thus serving as an important supplementary source of income for farms. However, with the advent of mechanization, mixed farming systems gradually declined, and farms became increasingly specialized, with separate operations focused on crop cultivation or livestock production.

With the decline of mixed farming systems, agricultural operations lost access to farmyard manures and simplified crop rotations, as forage crops were no longer required. These shifts in production practices resulted in a heavy reliance on chemical fertilizers and pesticides, which have had detrimental effects on soil and water quality and contributed to an increase in greenhouse gas emissions [4,5,11]. Livestock production transitioned into landless systems, with animal feed increasingly sourced from external supplies, thereby raising energy inputs related to feed preparation and transportation [102]. Concentrated livestock farming has become a major source of environmental pollution, contributing to nitrate and phosphate leaching into water systems, as well as significant emissions of enteric methane, ammonia, and other greenhouse gases into the atmosphere [13,15,16].

Integrating crop–livestock systems is strongly advocated as a strategy to rebalance agroecosystems. This approach boosts income and mitigates the environmental impact of agricultural and livestock activities. On one hand, animals are crucial in valorizing resources, such as grazing areas and crop residues, by converting them into food and non-food products. This practice's economic and environmental benefits are well-documented [103]. Crop–livestock integration is a key practice promoted by regenerative agriculture due to its substantial potential for soil regeneration [104]. Studies have demonstrated significant improvements in soil physical properties, increased organic matter content, and enhanced biological activity following the introduction and management of animals within agricultural systems [105,106].

Nevertheless, the primary challenge lies not in recognizing the potential benefits of integrating crop–livestock systems, but in reconciling this integration with the landholding structure and socioeconomic conditions of modern agricultural operations. In orchards and vineyards, for example, grazing animals during certain periods of the year can harm plant health, raising questions about how animals can be fed during these non-grazing intervals. Smallholder farming predominates in many regions of the world, with agricultural operations often consisting of micro-parcels dispersed across the landscape [107]. In such contexts, maintaining livestock necessitates the presence of a dedicated caretaker, such as a shepherd, regardless of herd size. Furthermore, many farms are small and do not generate enough income to sustain a household, with a significant proportion of agricultural activities occurring within a weekend farming model. In this system, farmers often engage in off-farm employment in urban areas and manage their properties during weekends, holidays, and other available periods [108]. One of the most significant challenges of regenerative agriculture will be the integration of livestock into farming systems, particularly without addressing the substantial increase in capital and labor requirements [109]. This challenge will be especially formidable in regions undergoing significant rural-to-urban migration [27,28]. Nevertheless, the benefits of successful integration will be substantial for those farmers who can implement it.

4. Effect of Key Regenerative Agriculture Practices on Agroecosystems

4.1. Effect on Soil

Soil erosion is one of the most pressing global environmental challenges. In addition to causing soil degradation, it contributes to the siltation of riverbeds and reservoirs, as well as to the eutrophication of aquatic ecosystems. Among the various soil degradation processes, erosion is particularly concerning due to its largely irreversible nature. Soil loss can occur rapidly, with a single event sufficient to displace tons of soil, whereas the pedogenetic processes responsible for soil formation are extremely slow [6]. Many practices that enhance soil coverage with vegetation, such as cover cropping, no-tillage, and others, are strongly endorsed by regenerative agriculture [29,31,37,38]. These practices effectively reduce soil erosion [17,18,98].

The principles of regenerative agriculture are primarily focused on soil regeneration through the enhancement of organic matter content, which is regarded as a central component of overall soil fertility [24,29,30]. The organic matter content is directly proportional to primary productivity within a given climate and soil context. The higher the productivity of the ecosystem, the greater the quantity of organic substrate deposited into the soil. The amount of organic substrate that becomes stabilized in the soil also depends on the rate at which it decomposes and is released into the atmosphere as carbon dioxide. Therefore, soil organic matter results from the balance between organic substrate inputs and its oxidation by heterotrophic microorganisms [6]. Inputs originate from photosynthesis products released into the soil, primarily through the plant root system, often associated with mycelia from mycorrhizal fungi and nitrogen-fixing microorganisms. Mycorrhizal fungi can account for up to 50% of the carbon entering the soil annually [110]. Animal manure and other organic materials added to the soil can also represent significant carbon inputs [111,112]. Regenerative agriculture, by advocating for cover crops and direct seeding techniques, contributes to increased organic substrate deposition and reduced soil aeration. These factors, in turn, help establish a balance conducive to higher soil organic matter content [6].

The organic substrate that undergoes humification in the soil forms complex interactions with clay minerals, forming humus–clay complexes. These compounds become progressively more resistant to microbial degradation and play a crucial role in soil structuring, significantly improving its physical properties. As a result, they create favorable conditions for root aeration and efficient drainage [113]. Soils with higher organic matter content also exhibit greater water-holding capacity and are less susceptible to compaction caused by the passage of machinery and equipment [114].

For various reasons, soils rich in organic matter typically provide more favorable conditions for plant growth. The organic substrate is the primary food source for soil food webs, supporting a diverse range of organisms, including earthworms, scarabaeids, millipedes, and numerous microorganisms. This diversity within the soil food web enhances soil health by reducing the likelihood of pathogenic organisms becoming dominant and causing plant diseases [58,115].

Regenerative agricultural practices enhance nutrient cycling, increasing plant nutrient availability. While the total amount of certain nutrients in the soil is often high, this does not always correlate with their bioavailability. Various soil factors, such as pH and organic matter content, influence nutrient bioavailability, affecting processes such as precipitation, solubilization, or chelation [6]. Growing plants typically reduce nutrient leaching, as observed with catch crops. Plant roots can absorb nutrients from deeper soil layers and redeposit them on the surface as crop residues or stubble, increasing the likelihood of nutrient reabsorption by roots, even those of plants with more superficial root systems [116,117].

Growing legumes, whether integrated into crop rotations, intercropping systems, or used as green manures, enhances nitrogen availability in the soil, benefiting both the intercropped species and subsequent crops in the rotation [118]. Their symbiotic relationship with nitrogen-fixing microorganisms enables legumes to access atmospheric nitrogen, an inexhaustible nitrogen source [42]. Additionally, in phosphorus-deficient soils, certain legumes can absorb phosphorus from sparingly soluble forms that are typically unavailable to most species [59,60]. Once incorporated into plant tissues, phosphorus is returned to the soil primarily in organic form, where it is released for subsequent crops through the activity of soil acid or alkaline phosphatases [59,61].

4.2. Effect on Functional Biodiversity and Trophic Chain Enrichment

Monoculture farming and using a limited number of high-yielding varieties within the same species result in reduced plant biodiversity. In contrast, crop rotation, intercropping, agroforestry, and cover cropping help diversify trophic chains. These practices also reduce the dominance of specific organisms within agroecosystems, thereby minimizing the likelihood of pest outbreaks and plant diseases [119,120].

Applying herbicides, which diminishes plant species diversity and significantly alters local flora, reduces soil organic matter and disrupts trophic chains within the soil ecosystem [121,122]. Similarly, broad-spectrum insecticides and fungicides harm non-target organisms, affecting microbial functions and altering community composition [122,123]. While pesticide use may offer short-term solutions to pest and disease problems, it disrupts the ecological balance by eliminating natural predators of pests. This creates a cycle where the recurrence of pests and diseases becomes more likely in subsequent cropping cycles [41,124].

4.3. Crop Productivity

Crop productivity is a crucial factor in the sustainability of agricultural operations. Generally, farmers sell their products at a fixed price per unit of mass and rarely possess the scale to influence market prices. Additionally, agricultural product prices are seldom determined by quality, except in small local markets, which lack the scale to become widespread. Any agricultural practice that does not prioritize the financial well-being of the farmer is unlikely to gain widespread adoption. Therefore, regenerative agricultural practices must ensure economic viability. A cover crop established in an orchard must balance the soil benefits it provides and the immediate competition it creates with the cash crop. Some studies have shown that cover crops can reduce tree productivity, even though they improve various aspects of soil fertility. This is particularly relevant in dryland fruit cultivation in semi-arid climates, where the risk of competition for water is high [85,99,125].

Farmers often recognize the benefits of direct seeding, but their main concern remains the potential for productivity loss, particularly in the short term. To address this, clear goals and practices must be established, and farmers need a solid understanding of the returns they can expect, whether in the short, medium, or long term. Increasingly, studies suggest that direct seeding not only maintains productivity but may even enhance it, alongside numerous benefits for soil quality and reduced operational time costs [46–48].

Establishing appropriate crop rotation is challenging for many regions and agricultural operations. Designing a four-year crop rotation with four main crops means that the gross margin of each crop must be relatively similar. Otherwise, farmers risk losing significant income when comparing the annual returns from the rotation with the monoculture of the species that currently yields the highest gross margin in the prevailing socioeconomic context. While the benefits of crop rotation are intuitive to most farmers, the potential income loss and increased technical complexity, often requiring additional equipment and expertise, are significant obstacles [64,65]. This is a critical consideration that regenerative agriculture should not overlook.

Intercropping and integrated crop-livestock systems generally offer higher productivity [85–87], but they come with significant challenges. These systems are often difficult to implement due to issues with mechanization or the need for specific land structures and labor resources, which may not be readily available in many regions [32].

4.4. Quality of Agricultural Products

The nutritional quality and density of foods, or their technological value for specific purposes, can be assessed in various ways. For example, a wheat cultivar might be prized for its high protein content, while grapes valued for wine production are typically selected for their high sugar content, which correlates with potential alcohol levels. However, these are exceptional situations; the most common scenario is that the quality of the products is not compensated for the producer [126,127].

Some antioxidant compounds, which are increasingly important in modern diets, are derived from secondary metabolites. These compounds often appear in higher concentrations when plants experience environmental stress, such as nutrient deficiencies, drought, or heat [128,129]. However, environmental stress can reduce plant productivity [130], raising concerns about how producers are compensated for their products, whether based on quantity or quality-related factors.

Studies within organic farming systems, including regenerative agriculture, have consistently highlighted the quality of products as a key benefit of these production methods [24,44]. However, a critical challenge lies in how the market values these products. Regenerative agriculture has been instrumental in raising consumer awareness about the importance of purchasing certified products. By doing so, consumers are made aware that their choices positively impact farms across various levels—environmentally, ethically, and socially [36]. Furthermore, regenerative agricultural practices focus on simultaneously enhancing both productivity and the quality of agricultural products.

5. Constraints and Challenges

For the adoption of regenerative agriculture practices to increase, awareness is crucial, though it may not be enough. Expecting producers to embrace practices that result in income loss is unrealistic. While some organic production methods are based on guidelines, they often rely heavily on an extensive list of prohibitions, as seen in the European Union's organic farming regulations (Regulation (EU) 2018/848) [131]. Regenerative agriculture, on the other hand, emphasizes practices that improve soil health, animal welfare, and social fairness [39] without imposing as many restrictive rules, making it easier to overcome adoption challenges and potentially reducing the risk of fraud.

Nevertheless, no-till practices will continue to advance in regions dominated by large-scale grain production. However, they will face challenges in areas with family farming and small landholdings, primarily due to the high cost of specialized equipment, which is often difficult to amortize. Implementing diverse crop rotations is also complex, particularly in regions with ecological constraints, where it is challenging to identify crops that match the income potential of those they replace. In horticulture, cover crops may compete for water and nutrients with cash crops, leading to reduced yields and income. Similarly, in perennial systems such as orchards and olive groves, selecting cover crops that enhance biodiversity and soil health without excessively competing with trees remains a significant challenge. While intercropping systems offer benefits, their limited compatibility with mechanization makes them more suitable for family farms where labor-intensive operations like harvesting are performed manually. Integrating crops and livestock presents further obstacles in sectors like viticulture and fruit growing, where grazing periods are restricted. Livestock feeding, in these cases, often relies on off-site grazing or purchased feed, which can be cost-prohibitive and less sustainable.

In addition to agronomic and logistical challenges, structural and environmental constraints can limit the feasibility of regenerative agriculture. Severe soil degradation, such as contamination with persistent pesticide or fertilizer residues, can undermine efforts to restore soil health. Changes in hydrological regimes, including the depletion of surface water or the alteration of natural waterways, may further constrain regenerative practices. The removal of natural buffers through deforestation reduces agricultural resilience, while land-use change from agriculture to industry, commerce, or housing leads to irreversible loss of arable land. Since regenerative agriculture often requires relatively extensive areas to fully express its principles, these structural limitations pose a serious barrier to widespread implementation.

To overcome these challenges, it is essential to prioritize targeted interventions. In the short term, improving access to knowledge, affordable equipment, and transitional financial support can facilitate initial adoption. In the long term, building resilient markets and policy frameworks that reward regenerative practices will be key. Farm-size-specific strategies are also necessary, as the constraints faced by smallholders differ significantly from those of large-scale operations.

Recognizing that farmers are unlikely to adopt practices that threaten their income, policymakers and certifying bodies have a pivotal role in mitigating these risks. Financial incentives, cost-sharing mechanisms, and market premiums for regenerative products can help offset the costs of transition. At the same time, consumer awareness and the credibility of certification schemes are crucial in stimulating demand and fostering a supportive environment.

While the global potential of regenerative agriculture is considerable, realizing this potential depends on coordinated, cross-sectoral efforts. Successful case studies from the Midwest and parts of Europe demonstrate that enabling conditions—such as supportive policies, accessible certification frameworks, strong farmer networks, and technological innovation—are fundamental. Future research should focus on designing regionally adapted transition pathways and implementation roadmaps to support the effective and equitable scaling of regenerative agriculture across diverse agricultural systems.

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