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REVIEW ARTICLE

Exploring the scope of ecosystem services in diverse farming systems for sustainable agriculture: A review

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Abstract

Ecosystem services (ES) are fundamental to promoting agricultural sustainability, playing a vital role in enhancing resilience and productivity within agricultural ecosystems. This review critically examines the interactions between biodiversity, farming practices and ES delivery, presenting a novel synthesis of their roles in sustainable agriculture. Unlike existing literature focussing on isolated ES or individual farming paradigms, this review integrates insights from multiple agricultural paradigms, including organic, regenerative and conventional systems. It provides a comparative assessment of their effects on biodiversity and ecosystem functionality. It also emphasizes the role of agricultural biodiversity as a nexus for enhancing ecosystem services. This review is structured into four main sections. It begins by classifying key ecosystem services relevant to agricultural systems, underscoring their importance for environmental sustainability. Second, it investigates various farming systems, with a particular focus on the role of biodiversity in enhancing ecosystem services. Third, it conducts a comparative assessment of diverse farming systems follows, evaluating their impacts on biodiversity and ecosystem functionality to inform evidence-based strategies for enhancing ES. This review bridges gaps in existing research by highlighting synergies and proposing strategies to optimize diverse farming systems. These efforts aim to enhance ecosystem services and contribute to sustainable agricultural landscapes.

Keywords: agroecosystem; biodiversity; ecosystem services; farming systems; sustainable agriculture

Introduction

Agriculture faces critical challenges, including biodiversity loss, eutrophication, pesticide pollution and soil degradation resulting from intensive farming practices, all of which demand sustainable solutions (1). Conventional farming, characterized by monocropping, synthetic inputs and intensive tillage, has increased short-term yields but disrupted essential ecosystem services such as biodiversity, nutrient cycling, pest regulation and carbon storage (2).

The ecosystem services framework, first introduced in 1981 and further developed through initiatives like the Millennium Ecosystem Assessment (MEA) (3), highlights the critical connection between human well-being and ecosystem health (4-6). The MEA, initiated by the United Nations, provided a comprehensive evaluation of the state of the world's ecosystems and their services. It aimed to inform decision-makers and the public about the consequences of ecosystem change for human well-being. The assessment underscored the rapid degradation of ecosystems due to human activities and emphasized the urgent need for sustainable management practices. Its findings have since influenced policy-making, research and global awareness, promoting the integration of ecosystem services into decision-making processes. These services, ranging from provisioning to regulatory and supporting services, are essential for agricultural sustainability. However, modern agricultural practices often degrade these services, making the transition to regenerative approaches increasingly urgent. This shift is crucial to address challenges such as biodiversity loss, climate change, water scarcity, and soil erosion (7–9).

In response to these challenges, agroecological approaches, including regenerative practices and organic farming, have gained importance. These practices integrate biodiversity and ecosystem services into farming systems (10). Regenerative agriculture employs techniques like crop rotation, cover cropping and managed grazing to restore ecosystem functions from the soil up, delivering broad benefits for biodiversity, carbon sequestration and soil health (11, 12). These regenerative practices focus on rebuilding soil organic matter and structure, which supports natural soil functions, improves yields, enhances water infiltration and reduces erosion (13).

Diversified farming systems strategically manage agrobiodiversity across multiple scales to enhance ecological resilience (14). By incorporating practices from organic and agroecological methods, these systems strengthen vital ecosystem services including soil health, nutrient cycling, pest control, carbon sequestration and water retention capacity. Agroecological farming integrates ecological principles to maintain yields while restoring ecosystem function (15). Key practices include reduced tillage, cover cropping, crop rotations and biodiversity conservation, which significantly enhance ecosystem services compared to conventional methods (11, 12).

Fundamental practices like no-till farming, compost application and managed grazing synergistically recycle nutrients, improve soil structure and stimulate soil carbon storage, leading to enhanced soil health and agricultural productivity (16, 17). More diverse farming systems, including agroforestry and multi-cropping, further boost ecosystem services by enhancing biodiversity, improving nutrient cycling, and building climate resilience through increased system complexity (10, 18, 19). For example, agroforestry systems increase bird diversity by 100%, with bird species richness more than doubling compared to open agricultural land (20). These integrated systems demonstrate how ecological principles can be successfully applied to create resilient and sustainable agricultural systems that benefit both food production and environmental conservation (Fig. 1).

Agricultural biodiversity serves as the cornerstone for delivering essential ecosystem services and significantly reducing dependency on external inputs through strategic preservation across ecological, spatial and temporal scales (21, 22). This approach encompasses key strategies such as integrated agroforestry systems that combine trees, crops and livestock; diverse polycultures that maximize land use efficiency and targeted habitat conservation for beneficial organisms that support natural ecosystem functions (18). These methods promote complex ecological interactions, enhance functional redundancy, improve system stability and build resilience to environmental stresses (10). Conservation biological control, implemented through strategic habitat management, effectively minimizes reliance on chemical insecticides by fostering and maintaining populations of natural predators and parasitoids, thereby enhancing natural pest regulation mechanisms (23).

Given the challenges of climate change and environmental degradation, transitioning to regenerative agricultural models (e.g., practices like no-till farming or agroforestry are essential for future sustainability (24). Scientific evidence demonstrates that regenerative methods have significant carbon sequestration potential, with global soils capable of storing an additional 114-242 Pg of carbon - a quantity substantially reducing atmospheric greenhouse gas concentrations (12). Agriculture both depends on and influences critical ecosystem services, including pollination, nutrient cycling and soil renewal (25). For example, studies have shown that approximately 40% of insect pollinator species are threatened with extinction, largely due to agricultural intensification (26). Amid escalating environmental crises, ecologically based farming systems have emerged as vital for food security and resilience (27).

Studies demonstrate that diverse farming systems provide substantial benefits, including improved soil quality, carbon sequestration, pest control and enhanced pollination (14). These systems support long-term productivity through improved ecosystem services (28), by enhancing carbon storage, reducing erosion and strengthening food security (29). Recent research highlights the economic benefits of diversified farming systems, such as reduced input costs, premium prices for organic products and enhanced farm resilience to market fluctuations. Furthermore, the increased on-farm biodiversity associated with these practices strengthens ecosystem resilience, supports pollinator populations and enhances natural pest control mechanisms, all of which are fundamental to sustainable agricultural systems (18).

Soil is being lost 10-40 times faster than it can naturally replenish due to unsustainable farming practices (30). This degradation is contributing to biodiversity loss, with conventional farming reducing species richness by 8.9% globally (31). Diversified and organic farming systems offer a solution by boosting species richness, improving soil health and enhancing ecosystem services. Diversified farming can increase species richness by 26%, particularly benefiting pollinators and predators (32). Organic farming increases species richness by 34% and abundance by 50% (33), while also improving crop species richness by 48% (34). Furthermore, integrating crop diversification in organic systems reduces yield gaps to just 8–9% (35). Transitioning to sustainable farming is crucial for preserving soil, maintaining biodiversity and ensuring long-term food security and productivity.

The integrated approach of regenerative agriculture represents a significant shift from conventional farming methods, offering a pathway to both productive and environmentally sustainable food systems. By focusing on soil health as the foundation for agricultural success, these practices create a positive feedback loop where improved ecosystem services support better crop yields and environmental outcomes simultaneously. This comprehensive approach not only increases agricultural productivity but also ensures long-term sustainability through ecological intensification and resilience building.

Different terms used in the ecosystem services (Table 1)

Classification of Ecosystem Services in Agricultural Systems

Ecosystem services can be categorized into 4 types (Fig. 2); provisioning, cultural, regulatory and supporting services (54).

Case study 1: Agroforestry and Payment for Ecosystem Services (PES)

Agroforestry systems in Asia and Africa have successfully implemented PES schemes, incentivizing farmers to maintain forest patches and convert degraded lands into productive agroforestry systems (39). These systems provide multiple ecosystem services, including air purification and soil enrichment (55).

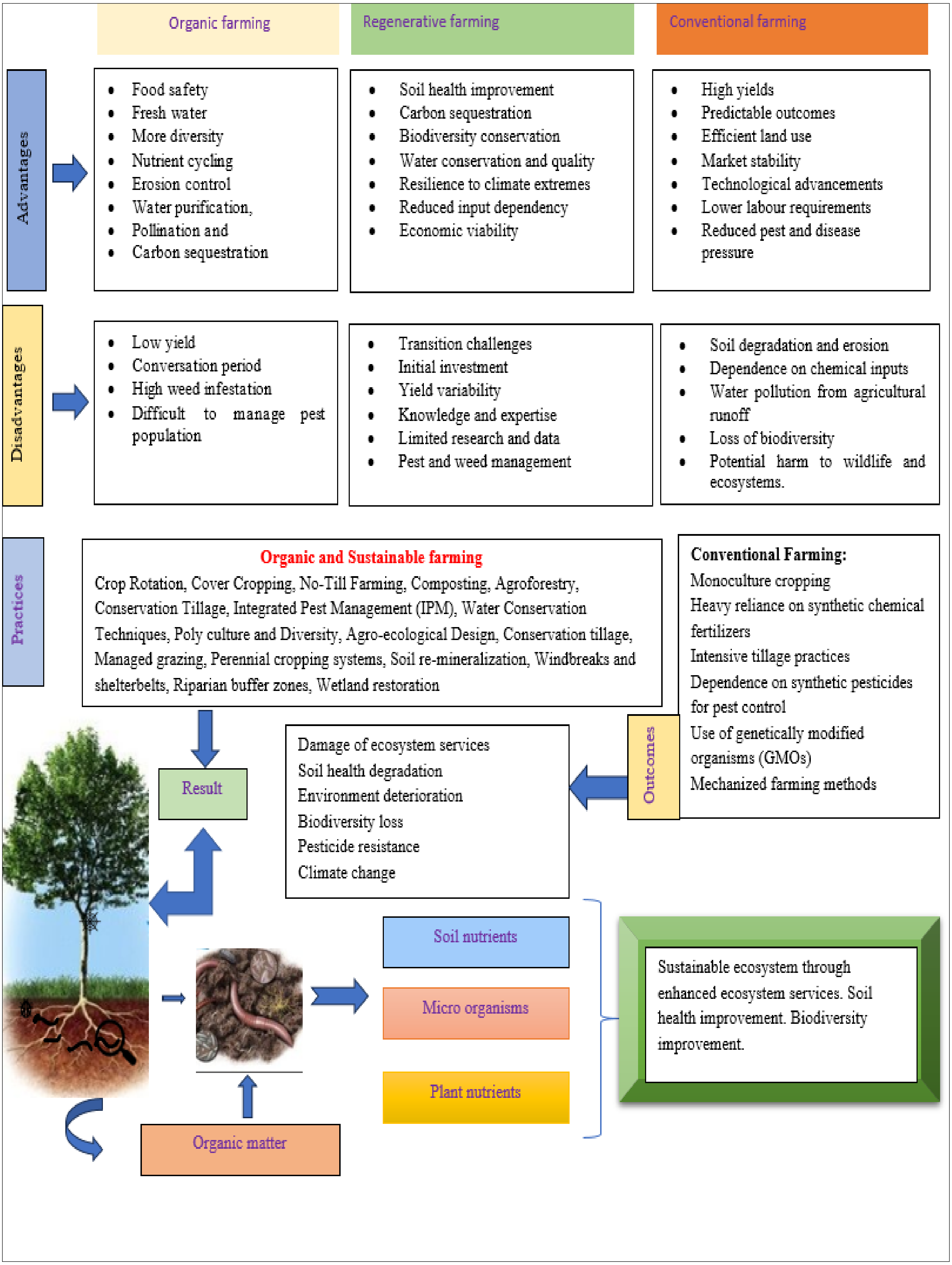

Fig. 1. This figure illustrates the comparative advantages and disadvantages of organic, regenerative and conventional farming systems in enhancing ecosystem services. Conventional farming practices, such as monocropping, heavy pesticide use and intensive tillage, often lead to soil degradation, biodiversity loss and reduced ecosystem resilience. In contrast, organic and regenerative farming adopt sustainable practices like crop rotation, reduced chemical inputs, cover cropping and agroforestry. These approaches improve soil health, increase biodiversity, enhance water infiltration and reduce greenhouse gas emissions. The figure highlights key practices under each system and suggests pathways to address conventional farming challenges through organic and regenerative techniques, ensuring the balance between productivity and environmental sustainability.

Table 1. Various terms used in ecosystem services

Terms	Definition	Reference
Agroecology	Ecological study of agricultural systems.	(36)
Ecosystem functions	The habitat, biological or system properties or processes of ecosystems.	(37)
Ecosystem health	The ability of an ecosystem to maintain key ecological processes, functions, biodiversity and productivity over time at sustainable levels.	(38)
Diversified Farming Systems (DFS)	Farming practices and landscapes that intentionally include functional biodiversity at multiple spatial and/or temporal scales to maintain ecosystem services that provide critical inputs to agriculture, such as soil fertility, pest and disease control, water use efficiency and pollination.	(21)
Agroforestry systems	Land management systems that intentionally combine trees and/or shrubs with crops and/or livestock in agricultural settings, accruing ecological and economic benefits.	(31, 32, 39)
Conservation agriculture	An approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security that promotes minimum disturbance of the soil, permanent soil cover with previous crop residues and crop species diversification.	(41-43)
Organic farming	A production system that sustains the health of soils, ecosystems and people relying primarily on ecological processes and microorganisms, biodiversity and cycles adapted to local conditions.	(44-46)
Regenerative agriculture	Farming and grazing practices that reverse climate change by rebuilding soil organic matter and restoring biodiversity – resulting in both carbon drawdown and improving the water cycle.	(47-49)
Conventional farming	Capital and input intensive farming system reliant on synthetic fertilizers and pesticides with monocultures focused on maximizing productivity and efficiency.	(14, 42,50)
Natural farming	An ecological farming approach using no external synthetic inputs that activates indigenous microorganisms and natural ecosystem services to optimize soil and plant health.	(51)
Precision agriculture	Farm management system using digital techniques to account for in-field variability aiming to optimize field-level management with respect to productivity and environmental impact.	(52)
Biodynamic farming	Spiritual-ethical-ecological approach to agriculture emphasizing holistic farm individuality, ethical economic associations and bioregulatory techniques connecting cosmic and earthly elements to maximize farm health.	(53)
Ecosystem Services functional Spatial Unit (ESSU)	It defines the smallest spatial unit that combines cultivated and wild biodiversity to support a wide array of ecosystem services, encompassing interactions among crops, trees, livestock, wildlife and semi-natural features like hedgerows and forest patches.	(54)

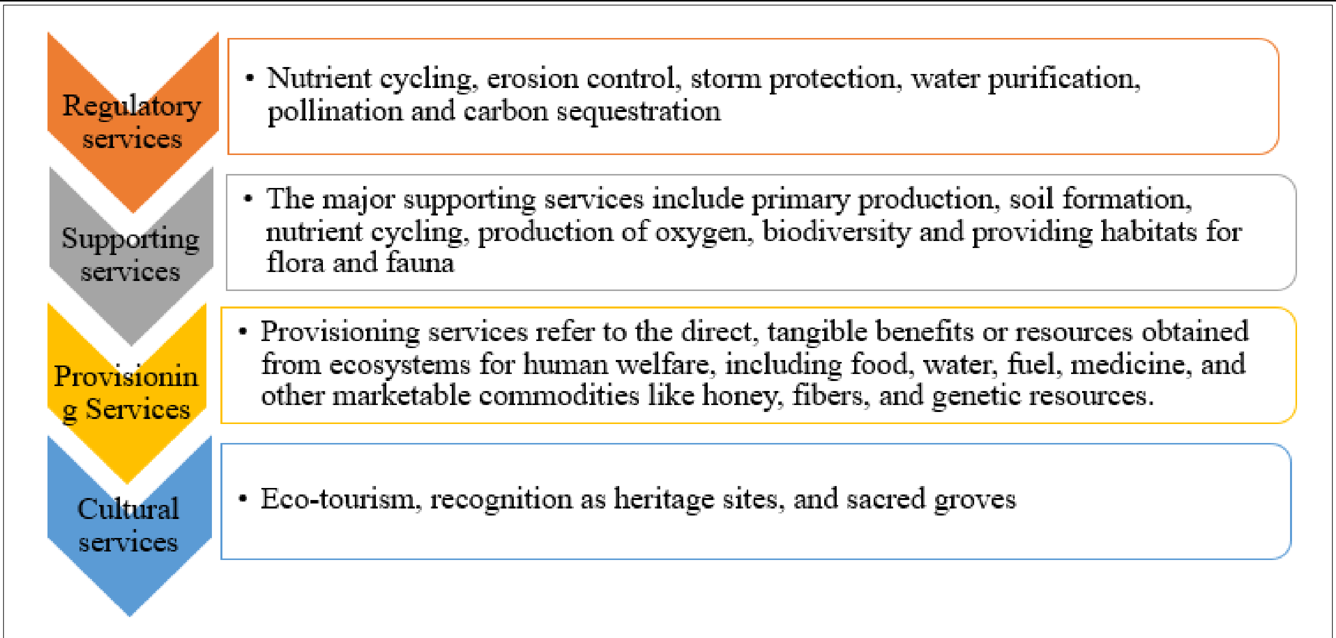

Fig. 2. Types of ecosystems services (sourced from 3, 47 and 48).

Case study 2: Groundwater Dependent Ecosystems (GDEs)

In California, GDEs support pollinator-dependent crops and carbon storage, demonstrating the importance of groundwater in sustaining agricultural productivity and ecological balance (56).

Case study 3: Pollination services in riparian zones

A study in Karnataka, India found that pollinator visitation rates decreased with distance from riparian zones. Bee colonies, mainly Apis dorsata and Apis cerana, were found in riparian zones, indicating their potential as pollinator habitats. Conservation of riparian zones was found to increase pollination services to adjacent coffee plantations. The study highlights the importance of preserving riparian zones for ecosystem services. Riparian zones can support biodiversity and pollination in agricultural landscapes (57).

Case study 4: Pest control services through biological control in Asian rice systems

A case study in the Greater Mekong Subregion introduced Integrated Pest Management (IPM) for rice production, funded by the European Union. The initiative established 12 *Trichogramma* spp. rearing facilities to control rice stem borers. Implementation resulted in 2-10% higher rice yields, increased natural enemy abundance and reduced insecticide applications.

The project promoted IPM practices among 50 trainers and 6400 rice farmers. The case study demonstrates the potential of advanced biological control-based IPM systems (58).

Diverse Farming Systems for Sustainable Agriculture

An agroecological transition is essential for placing food systems on sustainable trajectories yet it requires understanding the mechanisms in diverse farming models that might balance productivity gains with provisioning of ecosystem services (59). Multiple frameworks for sustainable intensification exist from integrating agroforestry, organic approaches, conservation agriculture or principles from ecology and circular economies - though comparisons across systems remain scarce (60). Crop diversification and targeted agrobiodiversity are known to promote ecological resilience and soil function (61). System modelling helps assess long-term trade-offs between yield and environmental impacts that empirical studies often overlook (62). Higher diversity in multiple cropping systems creates microhabitat differentiation, facilitating optimal species occupancy, promoting co-existence. This fosters beneficial interactions, mitigates weed dominance and enhances biological control mechanisms in open agroecosystem habitats (63). Diverse farming systems play a crucial role in sustainable agriculture and agroecosystems by providing a range of ecosystem services. These services include nutrient cycling, pest and disease regulation, erosion control, biodiversity conservation, and carbon sequestration. (54) The concept of Ecosystem Services functional Spatial Unit (ESSU) is a framework developed to facilitate the planning and assessment of agroforestry and intercropping systems by emphasizing their ability to provide ecosystem services. It defines the smallest spatial unit that combines cultivated and wild biodiversity to support a wide array of ecosystem services, encompassing interactions among crops, trees, livestock, wildlife and semi-natural features like hedgerows and forest patches (64).

Also, offers a tool for designing, modeling, monitoring and auditing ecosystem services in diversified agroecosystems (65). To promote diversified farming systems, it is important to understand their ecological and economic consequences. While diversified farming practices provide greater biodiversity and ecosystem services, the economic benefits may not always outweigh the costs in the short term (66) .

Biodiversity indices are essential tools for quantifying the variety and abundance of species within ecosystems (67). They help gauge the health and complexity of an ecosystem by evaluating aspects like species richness (the number of different species), species evenness (the distribution of individuals among species) and functional diversity (the range of biological functions performed by species). Common biodiversity indices include (68):

Shannon Index (H)

Measures both species richness and evenness. A higher Shannon Index indicates greater biodiversity.

Example: In Jamaica, the Shannon Index revealed a decline in crop diversification over time in mono-cropping systems, whereas multiple cropping systems in certain parishes maintained or increased crop diversification (69).

Simpson's Diversity Index (D)

Measures the probability that two randomly selected individuals belong to the same species. A lower D value indicates higher diversity.

Species Richness (S)

A count of species in an area, regardless of abundance.

Acoustic Indices

Emerging methods like acoustic indices offer a novel way to assess biodiversity by analysing soundscapes. However, their effectiveness as proxies for biological diversity remains debated, with studies showing variable results (70).

Role of Biodiversity, Soil Health and Other Ecosystem Services in Enhancing Agricultural Systems

Biodiversity is widely recognized as the cornerstone of productive and resilient agricultural systems (Table 2). Despite this recognition, quantifying the relationships between biodiversity, ecosystem stability, service provisioning and yield gaps remains a key research challenge. Addressing these concerns requires a complete understanding of ecological principles, climate adaptation and socio-economic trade-offs inherent in agricultural practices. Effective monitoring and management indicators are crucial for assessing the impacts of agroecological practices on ecosystem services (71). Below, are strategies to integrate biodiversity into agricultural systems, highlighting their benefits and trade-offs.

Agroforestry

Agroforestry integrates trees and shrubs into agricultural landscapes, providing multiple ecological and economic benefits. Trees enhance soil fertility, increase water retention and act as windbreaks, protecting crops from extreme weather events. Additionally, they support biodiversity by creating habitats for various species and fostering multi-trophic interactions essential for pest control (72).

Crop diversification

Crop diversification involves cultivating a variety of crops in a single farming system to improve functional trait diversity, stabilize yields and reduce risks of pest and disease outbreaks. Diversified systems enhance soil health and promote ecosystem services such as pollination and natural pest control (73).

Periphyton habitats such as vegetated strips or buffer zones between fields, play a crucial role in enhancing biodiversity, reduce erosion and act as natural barrier to pest and disease spread. These habitats also contribute to water quality improvement by filtering runoff (74).

Climate-resilient crop systems

Climate-resilient cropping systems leverage functional trait diversity to stabilize yields under variable weather conditions. Selecting drought-tolerant varieties or intercropping with species that enhance water-use efficiency are examples of strategies to mitigate climate change impacts (75).

Trade-offs

Implementing biodiversity-enhancing strategies in agriculture involves several trade-offs (24). Agroforestry systems require significant initial investments and long-term commitment, with potential competition for light, water and nutrients between

Table 2. Connecting agricultural biodiversity to ecosystem services

Key Findings on Agricultural Biodiversity's Role in	Practical Implications for Farming Practices	Reference
Increased landscape complexity and crop diversity enhanced biodiversity and pest control services on farms by supporting predator and parasitoid populations.	Encourages the adoption of diverse cropping systems and landscape-level planning to enhance natural pest control.	(81)
Crop diversification promoted soil biodiversity across organisms which provide key services like nitrogen cycling, organic matter decomposition and soil carbon storage.	Highlights the importance of integrating crop rotations and polycultures to maintain soil health and fertility.	(18)
Adding flowering field margins enhanced biodiversity of multiple taxa including pollinators like bees and wasps that provide crop pollination services.	Suggests implementing buffer strips or flowering margins to boost pollinator populations and improve crop yields.	(82)
Complex crop-livestock systems with enhanced biodiversity improved soil fertility and nutrient cycling functionality compared to specialized production.	Promotes mixed farming systems that integrate crops and livestock for better resource use efficiency and soil health.	(66)
Crop diversification strategies boosted productivity through ecological processes like complementarity in water and nutrient use between species.	Encourages the use of intercropping and multi-species cover crops to enhance resource use efficiency and farm resilience.	(83)
Crop rotations and intercropping practices supported weed regulation through increased competition and shifts in soil microbial communities.	Reinforces the value of crop rotation and intercropping for sustainable weed management and soil health.	(84)

trees and crops and necessitate additional farmer training. Crop diversification demands careful planning to align crop and variety combinations with environmental conditions and market demands, often involving increased labour and management complexity while providing lower short-term economic returns compared to monocultures (76). Allocating land for periphyton habitats reduces cultivation areas and requires additional maintenance, posing risks such as harbouring pests or invasive species if not managed effectively. Climate-resilient crop systems, while stabilizing yields under variable conditions, may have lower productivity during normal weather, requiring extensive research and extension services to balance short-term productivity with long-term resilience.

The concept of ecosystem services is central to conservation and environmental management, but practical implementation for land use planning faces challenges in quantifying biophysical trade-offs and considering socioecological aspects (77). The integration of ecosystem services into decision-making is crucial for framing conservation and restoration strategies and contributing to Sustainable Development Goals (SDGs) achievement (78, 79). As shown in Table 3, sustainable farming practices are essential for maintaining ecological balance, promoting biodiversity and ensuring long-term agricultural productivity. Achieving sustainable development involves transitioning ecosystem services from an abstract concept to implementable, socially equitable solutions supporting resilient socio-ecological systems under uncertainty (80).

Influence of Different Farming Practices to Ecosystem Services

Organic farming (OF) practices

Organic farming prohibits synthetic pesticide and fertilizer use, instead utilizing techniques like intercropping, biological pest control and compost application to manage soil fertility and pest pressure. Meta-analyses consistently demonstrate that on average, organic farming enhances biodiversity, soil organic matter, water infiltration rates and carbon sequestration compared to conventional agriculture (93). For example, organic farming sequestered 40% more soil organic carbon than integrated farming practices per ha per year (94). Organic farming practices have been shown to significantly enhance the resilience of agroecosystems (95). A vast number of studies have compared the yield, species richness, biodiversity, carbon sequestration differences between organic and conventional agriculture (34, 94, 96). There is, however, a lack of detailed understanding of how ES change and respond to different farming systems, management practices and biodiversity levels, particularly in the context of sustainable agriculture.

As shown in Table 4, organically managed soils often exhibit higher concentrations and stocks of soil organic carbon per ha, particularly in the topsoil layers, compared to conventionally managed systems. This increase in soil organic carbon is a key indicator of improved soil quality, reflecting the positive impact of organic farming on soil structure, nutrient cycling and overall ecosystem function. Additionally, the enhanced soil organic matter content in organic systems supports greater microbial diversity and activity, further

Table 3. Farming systems and their impact on ecosystem services

Farming System	Benefits for Biodiversity and Ecosystem Services	Examples	References
Organic farming	Increased species richness and abundance for birds, plants, insect pollinators, predatory insects across groups.	Higher species richness was identified in organic vs conventional fields for bees, spiders, syrphids, lacewings, ladybirds.	(85)
Agroecological systems	Enhanced biodiversity across taxa with beneficial spillovers from non-crop habitat.	Mixed crop-livestock systems hosted 40% more bee species than input intensive cereal monocultures.	(86–88)
Agroforestry	Additional niches and resources hosting more plants, insects, birds and mammals.	Silvo-arable integrating trees and crops supported 11-14 more ground beetle species than open croplands	(89)
Regenerative	Increased activity and species abundance for soil macrofauna like earthworms and isopods.	Long term no-till diversified cropping increased earthworm density by 38% over 20 years.	(90, 91)
Cover Crop Usage	Enriched resources augment rare and threatened farmland bird/insect foraging habitats.	Vegetative cover increased per-capita seed predation by 73% compared to bare plots which validate existing evidence suggesting that cover crops play a role in facilitating weed biocontrol.	(92)

Table 4. Contribution of organic farming practices to ecosystem services

Farming Practice	Effect	Ecosystem Services	Reference
Crop Rotation	Organic farming boosted higher biodiversity than conventional farming in 8 out of 10 cases, with an average increase in species richness of approximately 30%.	Supporting Services (Biodiversity, Habitats)	(34, 51)
Composting	Organic farming sequestered 40% more soil organic carbon than integrated farming practices per hectare per year.	Regulatory Services (Carbon Sequestration)	(94)
Manure Management	Use of green manure plants enhances alkali-hydrolyzable nitrogen and available phosphorus, improves microbial biomass carbon (MBC) and soil enzyme activities.	Regulatory Services (Nutrient Cycling) and Supporting Services (Soil Formation)	(113)
Integrated Pest Management (IPM)	Organic farming had significantly greater species evenness and richness of native bees and butterflies.	Supporting Services (Biodiversity, Habitats)	(114)
Cover Cropping	Strategic combination of cover crops, compost and no-till methods maximizes carbon sequestration, offering a promising approach for mitigating climate change.	Regulatory Services (Carbon Sequestration, Erosion Control)	(115)
Minimum Tillage or No-Till	Earthworm abundance and functional group diversity were significantly higher in zero tillage systems with mob-grazing.	Supporting Services (Soil Formation, Biodiversity)	(116)
Organic Amendments	Organic fertilizers provide a more balanced nutrient supply, improve soil physical conditions and sequester more soil organic carbon than chemical fertilizers.	Regulatory Services (Nutrient Cycling, Carbon Sequestration) and Supporting Services (Soil Formation)	(117, 118)
Biological Control	Organic farming had significantly greater species evenness and richness of native bees and butterflies.	Supporting Services (Biodiversity, Habitats)	(114)
Mulching	Organic farming practices sequestered 37.4% more soil organic carbon per year, while also improving soil structure.	Regulatory Services (Carbon Sequestration), Supporting Services (Soil Formation)	(119)
Livestock Management	Integrated livestock grazing and agroforestry practices improve soil health and biodiversity while sequestering more carbon.	Regulatory Services (Carbon Sequestration), Supporting Services (Soil Formation, Biodiversity)	(120, 121)
Agroforestry	Agroforestry systems enhance biodiversity and sequester more carbon, contributing to better soil health and ecosystem stability.	Supporting Services (Biodiversity, Habitats) and Regulatory Services (Carbon Sequestration)	(115, 120)
Minimum Use of External Inputs	Organic systems with minimal external inputs have been shown to maintain higher biodiversity and better soil health compared to conventional systems.	Supporting Services (Biodiversity, Soil Formation)	(94, 117)
Incorporating Native Species	Incorporating native species in farming systems enhances biodiversity and supports ecosystem resilience.	Supporting Services (Biodiversity, Habitats)	(116)
Adaptive Management	Adaptive management strategies in organic and regenerative farming enhance ecosystem services by optimizing practices based on real-time data.	Regulatory Services (Nutrient Cycling) and Supporting Services (Biodiversity)	(118, 120)
Focus on Soil Health	Practices that focus on soil health, such as composting, cover cropping and reduced tillage, significantly enhance soil formation and carbon sequestration.	Supporting Services (Soil Formation) and Regulatory Services (Carbon Sequestration)	(94, 119)
Biodiversity Conservation	Biodiversity conservation practices in organic and regenerative systems increase species richness and support habitats for flora and fauna.	Supporting Services (Biodiversity, Habitats)	(34, 51)

contributing to the sustainability and resilience of agroecosystems. Meta-analyses reveal that organic farming systems have higher soil organic matter content and promote both agro-biodiversity and natural biodiversity (97).

It was conducted a study focusing on the microbial dynamics in organic and conventional farming systems and their impact on soil-borne plant diseases (98). The research carried out in a long-term field experiment managed for 18 years, utilized amplicon sequencing to reveal a higher abundance of biocontrol genera and increased bacterial diversity in organic fields compared to conventional ones. The study further validated the disease suppressive potential through in planta experiments against *Rhizoctonia solani* and *Fusarium oxysporum*, demonstrating lower disease severity in plants treated with microbiome from organic fields. Key taxa such as *Flavobacterium*, *Bacillus*, *Pseudomonas* and *Planctomycetes* were identified with the potential to enhance disease-suppressive potential in organic fields. The findings suggest the prospect of developing synthetic microbial communities for inducing disease suppressiveness in otherwise conducive soils.

A study revealed the presence of 45 different bacteria morphologies, with a total population ranging from 20×10^9 to 20×10^{11} CFU/g (99). The combination of 20 kg of organic fertilizer and 100 ppm of salicylic acid demonstrated the highest bacterial diversity, providing novel insights into the abundance and diversity of bacteria in citrus plantations. A comparative study was conducted to assess the impacts of long-term organic (ORG) and conventional (CON) farming practices on bacterial and fungal biomass, microbial activity, soil CO_2 emission and nitrogen forms in *Helianthus annuus* L. cultivated soil (100). The study revealed that microbial biomass was more active and abundant in the organic system, which also exhibited higher soil CO_2 emissions. Despite being less abundant, fungi exhibited higher activity than bacteria in both systems. The ORG treatment showed significantly greater bacterial richness in 16S rRNA gene sequencing, with *Cyanobacteria*, *Actinobacteria* and *Proteobacteria* being the most abundant phyla. These phyla are critical for nutrient cycling and ecosystem functioning. However, the ORG sunflower yield was significantly less compared to CON, emphasizing the complex interplay between agricultural practices, microbial dynamics and crop productivity.

Regenerative farming practices

Distinct from organic farming, regenerative agriculture explicitly seeks to rehabilitate degraded soils and ecosystems through holistic land management. Beyond the production of goods, regenerative agriculture seeks to establish a robust and resilient farming system (47).

Regenerative agriculture (RA) can address urgent global challenges like environmental degradation, climate change and poverty by improving land use and agricultural practices. It involves building agricultural systems that are regenerative, biodiverse, climate-resilient, equitable and economically sustainable (12). RA practices like organic amendments, cover cropping and conservation tillage can increase soil organic carbon (SOC) stocks in Southeast Asian croplands. However, some practices may also increase greenhouse gas emissions, offsetting SOC gains. Further research and data sharing are needed to understand the net impact of regenerative agriculture on SOC and greenhouse gas emissions. Five principles that guide the approach are as follows:

✓ Minimise soil disturbance - Minimizing tillage and soil disturbance fosters the growth of beneficial microorganisms, enhancing soil health. This practice also boosts the soil's capacity to retain essential nutrients and water, improving overall fertility and resilience.

✓ Keep the soil covered year-round- Strong root systems promote soil biodiversity, facilitate nutrient cycling and enhance the soil's ability to retain moisture. Perennial crops play a crucial role in sustaining these living root networks, supporting long-term soil health and resilience.

✓ Keep live plants and roots in the soil for as long as possible.

✓ Incorporate biodiversity- Growing the same crop repeatedly in the same field depletes soil nutrients and creates favourable conditions for pests to thrive.

✓ Integrate animals - Livestock play a vital role in maintaining healthy soils and ecosystems. When managed correctly, grazing can enhance both soil and plant health.

RA practices improve soil productivity and health by restoring soil organic carbon (SOC) content. Besides increasing SOC, regenerative agriculture practices are also expected to restore soil fertility, increase crop yield and reduce greenhouse gas emissions from croplands (12). Increasing SOC with conservation tillage depends upon several factors including precipitation, soil depth, crop yield, stubble retention and decomposition rate (101).

No-till (NT) or reduced-till farming with native cover crops in regenerative agriculture enhances ecosystem services and economic indicators in rainfed almond crops. This approach performs best in sustainability, acceptance and stability compared to conventional management and seeded cover crops. Regenerative agriculture with native cover crops enhances biodiversity, soil health and water cycling while reducing erosion and increasing crop yields. This holistic method offers a viable alternative for farmers seeking to improve ecosystem services while ensuring economic viability through sustainable practices (102). NT farming enhances soil biological properties by sequestering more carbon and increasing SOC, leading to higher biological activity (103). While NT farming improves soil health, its impact on climate change mitigation is debated. It was suggested that its effects may be overstated, highlighting the need for further research (104).

Regenerative agriculture also promotes ecosystem resilience, improves water quality and enhances soil health. This approach reduces the need for synthetic fertilizers and pesticides, mitigating climate change impacts (105).

Natural farming practices

Natural farming is a holistic approach that avoids external inputs by building indigenous soil microbial communities through techniques such as fermented organic matter (106). However, transition barriers exist, including high labour demands for implementation and insufficient policy support to incentivize adoption. Combining elements of natural farming with agroecological innovations, such as crop diversification or agroforestry, tailored to local contexts, could provide simultaneous productivity, ecological and social benefits.

In Iowa, researchers found that integrating prairie strips with varying coverage levels into conventionally managed corn -soy landscapes significantly increased site diversity, including birds, pollinators and predators of crop pests (51, 107). The benefits increased proportionally with the amount of natural habitat added. The researchers suggest integrating small amounts of perennial habitat strategically within commodity cropland could strike an optimal balance between maintaining crop production and supporting biodiversity.

Conventional farming practices

Conventional farming relies heavily on synthetic fertilizers, pesticides, mechanization, monocultures and extraction of water resources to maximize yields. These practices have contributed to declines in key ecosystem services globally, including loss of crop genetic diversity, decreased water quality from nutrient runoff, altered pollinator communities, soil degradation and rising carbon emissions (108). Incremental tweaks such as those offered by precision agriculture, are unlikely to reverse current negative trends without addressing the root causes. More transformational shifts addressing root causes are needed to transition conventional agriculture toward integrated systems grounded in agroecology (109).

Human activities have strongly modified ecosystems and biodiversity since the Neolithic Age. Over-exploitation of natural resources has led to the loss of habitats and species, consumption of fossil fuels, urbanisation, industrialisation and agricultural intensification. These factors have collectively increased human impact on all ecosystems. Such alterations could impact major ecological functions .

A study in western France, emphasizing the crucial balance between economic considerations and environmental concerns in weed control for crop production (110). The researchers explored the increasing pressure on farmers 'to reduce herbicide usage due to growing environmental risks associated with these chemicals. By analyzing 150 winter wheat fields, their Bayesian hierarchical model, which considered farmers' behaviour, revealed no significant relationship between herbicide use and crop yields. Surprisingly, herbicides were found to be more effective against rare plant species than abundant weeds, suggesting that herbicide application may not be as targeted as assumed. The study suggests that a 50% reduction in herbicide usage could sustain crop production while promoting both food security and weed biodiversity in intensive agriculture.

A study focusing on enhancing the sustainability of agriculture by evaluating natural processes crucial for crop production, such as pollination and pest control (111). The research, conducted in arable fields surrounded by species-rich field margins, examined the spatial dynamics of pest control for wheat aphids and the relationship between oilseed rape yield gains and pollinator visitation. The study found that species-rich field margins significantly enhanced natural pest control, with effects extending up to 50 m into the crop demonstrating the wide-reaching benefits of biodiversity. While oilseed rape yield gains were correlated with pollinator visitation, there was no evidence that yield benefits declined with distance from the crop edge. The results suggest potential strategies for integrated crop management globally, emphasizing the importance of targeted pesticide applications to support biodiversity-mediated ecosystem services and minimize environmental harm.

Although further in-depth research across various production contexts is essential, existing studies indicate that transitioning to diversified systems grounded in ecological principles, such as organic and natural farming methods, shows potential for balancing productivity, input efficiency and key ecosystem services more effectively than conventional farming focused primarily on yield. These systems show heightened potential for soil carbon accumulation, biodiversity preservation, water quality regulation and sustained resilience over time.

Multiple meta-analyses and long-term experiments comparing conventional agriculture to more diversified agroecological systems generally show enhanced ecosystem services in systems like organic farming, agroforestry, intercropping and other approaches grounded in biodiversity and natural soil processes (18, 72).

Meta-analyses consistently demonstrate positive correlations between farm-level plant, insect and soil biodiversity and both productivity and ecological sustainability over time across contexts from smallholder systems to large commercial operations (18). Valuing ecosystems solely through economics is inadequate, as it fails to capture their true importance to society. Biology, not economics, can determine the significance of natural environments, as it reflects the intrinsic value and functions ecosystems provide to society. Economics can help design institutions that promote conservation and provide incentives for protecting ecosystems. This approach can ensure the long-term sustainability of natural environments (112).

Deliberation

The growing emphasis on sustainable agriculture highlights the need for farming systems that balance productivity with the provision of essential ecosystem services, which are crucial for long-term food security and resilience. However, quantifying the impact of regenerative agriculture on ecosystem services remains a knowledge gap (122). Recent research underscores the transformative potential of alternative farming models that diverge from conventional, input-intensive practices.

Unlike traditional farming, which often prioritizes short-term yield gains, regenerative and organic approaches, rooted in ecological principles have been shown to enhance sustainability in the long run. Investigating the role of biodiversity in enhancing ecosystem services is crucial for understanding the complex interactions between ecological factors influenced by different agricultural practices.

The integration of diverse and sustainable agricultural practices, such as agroecology, agroforestry and regenerative farming, not only begets habitat creation but also champions the conservation of beneficial insects. Examining the trade-offs between ecosystem services and agricultural productivity is crucial to develop effective strategies for sustainable agriculture (123).

Exploring the role of ecosystem services in these diverse farming systems reveals a complex interplay of ecological dynamics influenced by various agricultural practices. Soil health is prioritized through ecologically informed practices such as crop rotation, cover cropping and reduced tillage, which collectively enhance soil organic matter, improve soil structure and augment water infiltration. These strategies, rooted in ecological principles, optimize soil conditions to support sustainable agricultural productivity. The importance of ecosystem services in sustainable agriculture is clear and undeniable. Excessive reliance on synthetic fertilizers and pesticides harms soil and aquatic ecosystems, leading to a rapid decline in biodiversity (124). This underscores the need for sustainable agricultural practices that prioritize ecosystem services and soil health to mitigate environmental degradation and promote ecological resilience.

Regenerative agriculture practices, as delineated (47), synergistically elevate agricultural yields, fortify soil health and confer resilience against pests and diseases. Developing effective monitoring and assessment methods for ecosystem services is necessary to evaluate the impact of these practices.

Organic farming, which relies on ecologically based cultivation practices, holds significant potential for enhancing biodiversity conservation, soil quality and carbon sequestration compared to conventional approaches (94). Meta-analyses have shown significant increases in species richness and abundance across taxa, as well as higher annual rates of soil carbon accumulation under organic management (33). While there are trade-offs in yields, ecosystem service gains can offset lower average productivity (45). To apply ecological insights to practice, it is crucial to integrate ecosystem services into agricultural decision-making. The wider adoption of agroecological approaches oriented around ecology, biodiversity and complex farm design also promotes multiple ecosystem functions from soil conservation to climate change resilience (36, 72). Heterogeneous farming systems, which offer habitat diversity, support vertebrate pest regulation and reduce the need for chemical inputs, contribute to more sustainable agricultural practices. Understanding the policy and governance frameworks that support the promotion of ecosystem services is vital to encourage the adoption of organic farming practices.

By connecting ecological principles with food production, farming models like perennial polycultures, silvopasture, conservation agriculture and agroforestry enhance carbon sequestration, nutrient retention and microclimate regulation, outperforming conventional monoculture systems. These diverse systems also help prevent pest outbreaks and improve production under varying climate conditions. While input-intensive systems still yield more on average, diversified systems offer a better balance across provisioning, regulating, supporting and cultural ecosystem services (12, 40).

Biodiversity is integral for securing productive agriculture over the long term by enabling services like soil fertility, pest regulation and plant pollination (18). Strategies that increase landscape complexity, crop diversification and genetic diversity directly translate into ecological processes that replace costly external inputs (83).

Conclusion

In conclusion, the critical review of ecosystem services influenced by diverse farming systems highlights their numerous benefits, including enhanced biodiversity, improved soil health and increased climate resilience. These systems, such as intercropping, agroforestry and crop rotations, promote ecological balance, sustainable productivity and economic and social benefits. However, challenges such as higher labour demands, management complexities, short-term yield reductions and limited market access for small-scale farmers remain significant barriers to their widespread adoption. Addressing these issues is essential to fully harness the potential of diverse farming systems.

Farmers can adopt locally relevant practices like intercropping and agroforestry, supported by training to enhance sustainable methods. Policymakers should provide targeted incentives, improve market access and align agricultural and environmental policies to promote long-term sustainability. Researchers must collaborate with farmers to develop practical solutions and integrate traditional knowledge with scientific innovations. A collaborative effort among these stakeholders is essential to overcome challenges, ensure food security and create resilient, environmentally sustainable agroecosystems.

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Authors' contributions

KL, ES and MS were responsible for conceptualization, writing the original draft and conducting the review and editing. RK, PJ and EP contributed to writing, reviewing and editing the manuscript. MA and NV participated in editing the manuscript. All authors have read and approved the final version of the manuscript.

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