

REVIEW PAPER

Beyond Yield: Integrating Ecosystem Services and Digital Regenerative Agriculture for Sustainable Food Systems

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Received: 16-04-2026

Revised: 19-05-2026

Accepted: 06-06-2026

ABSTRACT

Agriculture is increasingly challenged by climate change, land degradation, biodiversity loss, and declining ecosystem resilience, exposing the limitations of productivity-centric farming systems. Conservation Agriculture (CA) has provided a robust framework for resource conservation through minimum soil disturbance, permanent soil cover, and crop diversification. More recently, Regenerative Agriculture (RA) has emerged as an outcome-oriented approach that seeks to restore ecosystem functions, enhance biodiversity, and strengthen climate resilience. However, the relationship between CA and RA remains conceptually unresolved. Here, we argue that ecosystem services provide the missing link between these two frameworks. Moving beyond yield as the dominant indicator of success, we propose that soil carbon dynamics, biodiversity conservation, water regulation, nutrient cycling, and pollination support should serve as core metrics for evaluating agricultural sustainability. We further highlight the emergence of Digital Regenerative Agriculture, in which artificial intelligence, remote sensing, sensor networks, and digital soil monitoring enable the quantification and optimization of ecosystem outcomes at unprecedented scales. Despite growing enthusiasm, significant challenges remain, including inconsistent definitions, uncertain carbon sequestration estimates, regional variability, adoption constraints, and the risk of greenwashing. We contend that the future of sustainable agriculture lies not in choosing between conservation and regenerative paradigms, but in integrating both within ecosystem-service-based and digitally enabled management frameworks. Such a transition may represent a fundamental shift toward resilient, measurable, and climate-adaptive food systems. Ecosystem-service assessment coupled with digital regenerative agriculture provides a new framework for evaluating agricultural sustainability.

HIGHLIGHTS

- ① Ecosystem-service delivery is proposed as a unifying metric for sustainable agriculture.
- ② Regenerative agriculture extends conservation agriculture from resource conservation to ecosystem restoration.
- ③ Digital Regenerative Agriculture enables outcome-based management through AI, remote sensing, and digital monitoring.

How to cite this article: Mondal, P., Sarkar, A.K., Sarkar, J.D., Chatterjee, R., Kumari, G., Ray, D.P. and Paul, T. (2026). Beyond Yield: Integrating Ecosystem Services and Digital Regenerative Agriculture for Sustainable Food Systems. *Int. J. Bioresource Sci.*, 13(01): 157-164.

Source of Support: None; **Conflict of Interest:** None



- ① Current uncertainties surrounding carbon sequestration and regenerative claims require robust assessment frameworks.
- ① Integrating ecosystem services with digital technologies may transform sustainable agriculture into a measurable, resilience-driven system.

Keywords: Ecosystem-Service-Centric Agriculture, Digital Regenerative Agriculture, Climate Resilience, Soil Carbon Dynamics, Sustainable Land Stewardship

Agriculture is at the forefront of the climate and sustainability crisis. Rising temperatures, increasing climate variability, land degradation, biodiversity loss, and declining resource-use efficiency are placing unprecedented pressure on global food systems (Roy and Mondal, 2023). At the same time, decades of intensive agricultural practices have depleted soil organic matter, disrupted ecosystem processes, and reduced the resilience of agroecosystems to environmental stress (Sher *et al.* 2024). These challenges have exposed the limitations of conventional productivity-oriented agriculture and highlighted the need for approaches that simultaneously enhance food production, ecosystem integrity, and climate resilience.

Conservation Agriculture (CA) emerged as a major paradigm for sustainable intensification through its emphasis on minimal soil disturbance, permanent soil cover, and crop diversification (Chatterjee *et al.* 2023). Although CA has demonstrated substantial benefits for soil conservation, water-use efficiency, and resource management, its evaluation has largely remained centered on productivity and soil-related indicators. Increasingly, however, there is recognition that agricultural sustainability must be assessed through a broader ecological lens. This shift has accelerated interest in Regenerative Agriculture (RA), an outcome-oriented framework that seeks to restore ecosystem functions, enhance biodiversity, rebuild natural capital, and strengthen resilience to environmental change (Newton *et al.* 2020; O'Donoghue *et al.* 2024). Simultaneously, advances in artificial intelligence, remote sensing, and digital monitoring are enabling the quantification of ecological outcomes at unprecedented scales.

This review argues that the next frontier of sustainable agriculture lies in integrating conservation principles, regenerative practices, ecosystem-service assessment, and digital technologies. We propose that ecosystem services provide the critical link between CA and RA and that their measurement through emerging digital tools may underpin a new

generation of climate-resilient, ecosystem-service-centric agricultural systems.

Conservation Agriculture versus Regenerative Agriculture: Evolution or Revolution?

Conservation Agriculture (CA) and Regenerative Agriculture (RA) are increasingly positioned as pathways toward sustainable and climate-resilient food systems, yet their relationship remains contested. CA is founded on three operational principles—minimal soil disturbance, permanent soil cover, and crop diversification—that aim to enhance resource-use efficiency, soil conservation, and long-term productivity (Angon *et al.* 2019). Over the past four decades, CA has become a cornerstone of sustainable intensification and climate-smart agriculture.

Regenerative Agriculture has emerged more recently as a broader and less clearly defined framework. Rather than prescribing specific practices, RA is generally characterized by its intended outcomes, including improvements in soil health, biodiversity, ecosystem services, and ecological resilience (Newton *et al.* 2020; Giller *et al.* 2021). This outcome-oriented perspective has fueled debate over whether RA represents a genuinely novel paradigm or simply an expansion of existing conservation and agroecological principles. While advocates emphasize ecosystem regeneration, multifunctionality, and landscape-scale resilience, critics argue that many regenerative practices have long been embedded within CA and related agroecological systems (Giller *et al.* 2021).

A more meaningful distinction may lie in how success is measured. Historically, CA has been evaluated through indicators such as soil conservation, resource-use efficiency, and productivity. In contrast, RA increasingly prioritizes ecosystem-service delivery, including biodiversity conservation, nutrient cycling, water regulation, carbon dynamics, and resilience to environmental stress. This shift reflects a broader recognition that



agricultural sustainability cannot be adequately assessed through yield alone. Recent advances in digital agriculture further reinforce this transition. Artificial intelligence, remote sensing, digital soil mapping, and ecosystem monitoring tools now enable the quantification of ecological outcomes at unprecedented spatial and temporal scales (O'Donoghue *et al.* 2024). Consequently, RA is evolving from a management philosophy into a measurable framework for ecosystem stewardship.

Viewed through this lens, the debate is not whether RA replaces CA, but whether sustainable agriculture is transitioning from a paradigm centered on resource conservation to one focused on ecosystem regeneration. Rather than competing frameworks, CA and RA are best understood as complementary stages along a continuum of sustainable land management, with digital technologies increasingly bridging the gap between conservation, restoration, and resilience (Table 1).

Table 1: Critical comparison of conservation agriculture (CA) and regenerative agriculture (RA)

Dimension	Conservation Agriculture (CA)	Regenerative Agriculture (RA)	Critical Perspective
Primary objective	Conservation of soil, water, and agricultural resources	Regeneration of ecosystem functions and natural capital	RA expands the scope of CA from resource protection to ecosystem restoration.
Conceptual basis	Principle-based approach centered on three core practices (minimum tillage, residue retention, crop diversification)	Outcome-based approach focused on soil health, biodiversity, resilience, and ecosystem services	CA emphasizes prescribed practices, whereas RA emphasizes measurable ecological outcomes.
Soil management	Minimizes soil disturbance and erosion	Enhances biological activity, soil organic matter, and ecological functioning	Both promote soil health, but RA places greater emphasis on biological regeneration.
Biodiversity focus	Indirect benefits through crop diversification and reduced disturbance	Explicit objective involving above- and below-ground biodiversity enhancement	Biodiversity conservation is often a secondary outcome in CA but a primary target in RA.
Carbon sequestration	Focuses on maintaining and increasing soil organic carbon	Views carbon sequestration as one component of broader ecosystem regeneration	RA adopts a more holistic perspective beyond carbon-centric assessments.
Evaluation metrics	Crop productivity, soil conservation, water-use efficiency, soil organic carbon	Ecosystem services, resilience, biodiversity, soil health, social and environmental outcomes	RA advocates broader sustainability indicators beyond yield performance.
Cropping system diversity	Crop rotation and cover cropping encouraged	Highly diversified systems including cover crops, livestock integration, agroforestry, and perennial species	RA generally promotes greater system complexity.
Livestock integration	Often absent or optional	Frequently considered an integral component of nutrient cycling and ecosystem restoration	Integration of livestock represents a major distinction in many RA systems.
Landscape perspective	Primarily field-scale management	Farm-to-landscape-scale ecosystem management	RA adopts a broader socioecological framework.
Technology integration	Traditionally practice-oriented with limited technological dependence	Increasingly supported by AI, remote sensing, digital soil monitoring, and precision agriculture	Digital tools are becoming central to monitoring regenerative outcomes.
Climate resilience	Improves resilience through soil moisture conservation and reduced degradation	Enhances adaptive capacity through ecosystem restoration and functional diversity	RA potentially offers greater long-term resilience through multifunctionality.
Scientific consensus	Well-defined principles and extensive empirical evidence	Definitions and implementation frameworks remain under development	Lack of standardization remains one of the major challenges facing RA.
Overall characterization	Resource-conserving agricultural system	Ecosystem-regenerating agricultural framework	RA can be viewed as an evolutionary extension of CA rather than a completely separate paradigm.

Ecosystem Services as the Missing Link

The sustainability of agricultural systems cannot be assessed through productivity alone. Although yield remains essential for food security, it provides only a partial measure of agricultural performance because it overlooks the ecological processes that sustain production over time. Increasingly, ecosystem-service delivery is being recognized as a more comprehensive framework for evaluating both Conservation Agriculture (CA) and Regenerative Agriculture (RA), shifting the focus from short-term outputs to long-term ecosystem functionality (Newton *et al.* 2020; Sela *et al.* 2024).

Among ecosystem services, soil carbon occupies a central position because it underpins multiple soil functions, including nutrient retention, water-holding capacity, structural stability, and biological activity. Practices such as reduced tillage, residue retention, and diversified cropping systems enhance soil organic carbon stocks while strengthening ecosystem resilience (Dey and Mondal, 2020; Sarkar *et al.* 2023). Emerging evidence suggests that the value of regenerative systems lies not simply in carbon accumulation but in their capacity to restore ecological processes and adaptive capacity under environmental stress (Amundson and Biardeau, 2018; O'Donoghue *et al.* 2024).

Beyond soil carbon, biodiversity, water regulation,

nutrient cycling, and pollination collectively determine the resilience and stability of agroecosystems. Agricultural diversification can simultaneously enhance biodiversity, ecosystem functioning, and economic returns without compromising productivity, challenging the long-standing assumption that conservation and production are competing objectives (Tamburini *et al.* 2020; Raveloaritiana and Wanger, 2024). Likewise, improvements in soil biological activity, hydrological regulation, and pollinator support contribute substantially to climate adaptation and long-term resource sustainability (Garibaldi *et al.* 2021; Sher *et al.* 2024).

A key insight emerging from recent research is that resilient agricultural systems are defined less by their capacity to maximize yields than by their ability to sustain ecosystem functions under changing environmental conditions (Schreefel *et al.* 2020; Sela *et al.* 2024). Consequently, future assessments should prioritize multidimensional indicators encompassing soil carbon dynamics, biodiversity, water regulation, nutrient cycling, and pollination services rather than yield alone. Such a transition from yield-centric to ecosystem-service-centric evaluation may represent one of the most significant conceptual advances in sustainable agriculture (Fig. 1), providing a common framework

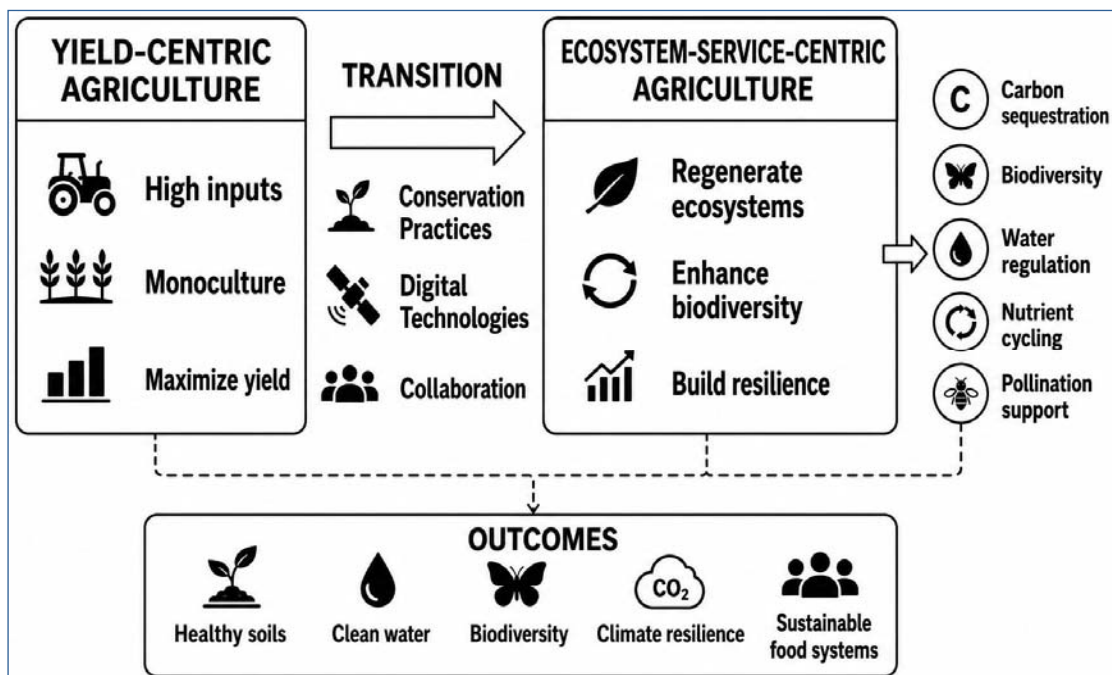


Fig. 1: Transition from Yield-Centric Agriculture to Ecosystem-Service-Centric Agriculture



through which CA, RA, and future agricultural innovations can be objectively assessed (Roy and Mondal, 2023).

Digital Technologies Enabling the Next Generation of Conservation Agriculture

The convergence of digital innovation and sustainable land management is redefining the future of Conservation Agriculture (CA). Traditionally centered on minimum soil disturbance, residue retention, and crop diversification, CA is increasingly evolving into a data-driven framework capable of monitoring, quantifying, and optimizing ecosystem outcomes. This emerging paradigm, termed Digital Regenerative Agriculture (DRA) (Fig. 2), integrates ecological restoration with precision technologies, shifting agricultural management from practice-based implementation to outcome-based stewardship (O'Donoghue *et al.* 2024).

Artificial intelligence (AI), remote sensing, and sensor networks are transforming the assessment of soil health and ecosystem functioning. Machine-learning algorithms can integrate soil, climate, and management datasets to predict soil carbon dynamics, nutrient availability, and crop responses, enabling site-specific interventions and adaptive management (Capetz *et al.* 2024). Simultaneously,

satellite observations, UAVs, and hyperspectral sensing provide near-real-time information on vegetation dynamics, soil moisture, land-use change, and environmental performance across multiple scales (Liakos *et al.* 2018; Benos *et al.* 2021).

Advances in the Internet of Things (IoT) further enhance resource-use efficiency through continuous monitoring of soil and crop conditions, supporting precision irrigation and climate-resilient decision-making (Babar and Akan, 2024). Perhaps most transformative is the emergence of digital soil-carbon monitoring, where machine learning, geospatial analytics, and spectral sensing enable scalable monitoring, reporting, and verification (MRV) of ecosystem outcomes, supporting carbon markets and climate-smart agriculture initiatives (Sachin *et al.* 2026).

The next frontier lies in decision-support systems that integrate AI, remote sensing, digital twins, and predictive analytics into unified platforms for ecosystem management. Such technologies enable continuous assessment of soil health, biodiversity, water regulation, and carbon sequestration, thereby linking agricultural productivity with ecosystem restoration. The integration of these tools establishes the foundation for DRA, where resilience, sustainability, and environmental

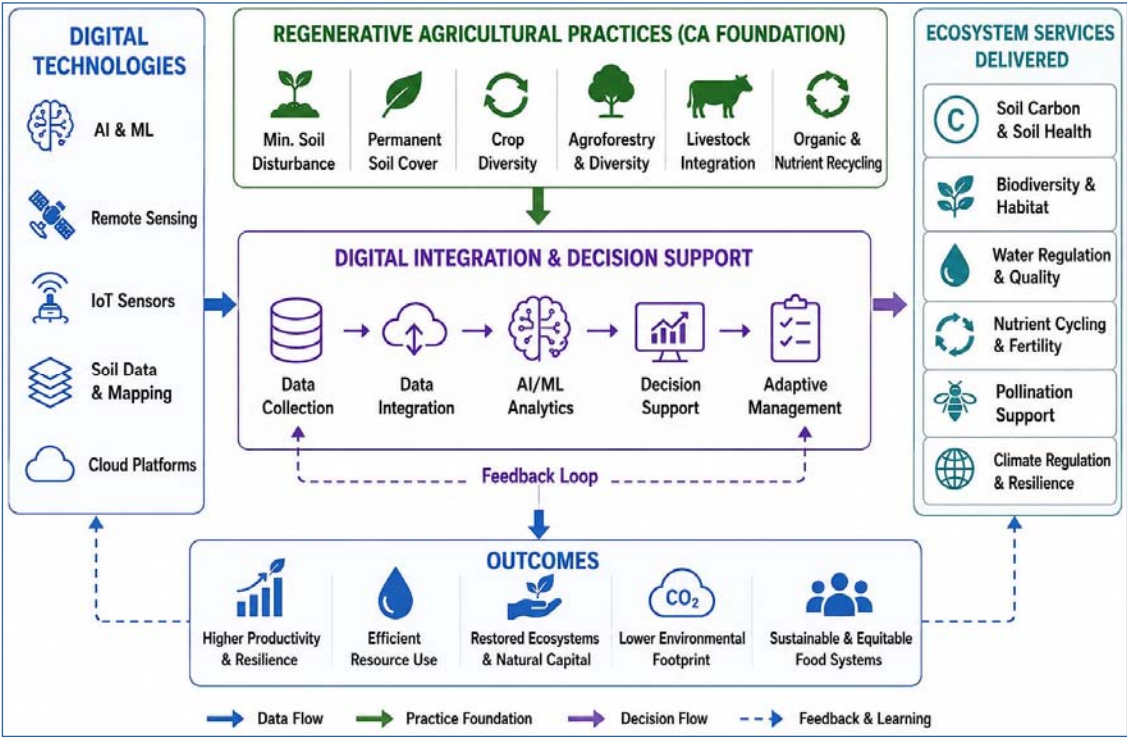


Fig. 2: Conceptual Framework of Digital Regenerative Agriculture

Table 2: Emerging Digital Technologies Supporting Ecosystem-Based Agricultural Management

Technology	Principle/Application	Ecosystem Services Supported	Major Benefits	Current Limitations
Artificial Intelligence (AI) and Machine Learning (ML)	Analysis of large datasets for predictive soil, crop, and environmental management	Soil carbon sequestration, nutrient cycling, climate resilience	Site-specific recommendations, improved resource-use efficiency, predictive decision-making	Data quality dependence, algorithm transparency, high computational requirements
Remote Sensing (Satellite, UAV, Hyperspectral Imaging)	Monitoring vegetation, soil conditions, water status, and land-use dynamics	Carbon storage, biodiversity conservation, water regulation	Large-scale monitoring, real-time assessment, reduced field sampling costs	Resolution constraints, cloud interference, need for validation
Internet of Things (IoT)-Based Sensors	Continuous monitoring of soil moisture, temperature, nutrients, and environmental parameters	Water regulation, nutrient cycling, soil health maintenance	Real-time management, precision irrigation, reduced resource wastage	Infrastructure requirements, maintenance costs, connectivity issues
Digital Soil Mapping (DSM)	Spatial prediction of soil properties using geospatial and environmental data	Soil carbon storage, nutrient retention, land-use planning	High-resolution soil information, targeted interventions, landscape-scale planning	Model uncertainty in heterogeneous environments
Digital Soil Carbon Monitoring Systems	Integration of sensors, spectroscopy, remote sensing, and AI for SOC assessment	Carbon sequestration, climate regulation, soil health	Efficient monitoring, supports carbon-credit schemes and MRV frameworks	Standardization and validation challenges
Decision-Support Systems (DSS)	Integration of environmental, agronomic, and economic data for management recommendations	Multiple ecosystem services	Improved management decisions, risk reduction, adaptive planning	User training and technology adoption barriers
Digital Twins and Simulation Models	Virtual representation of agricultural systems for scenario analysis	Climate resilience, resource conservation, ecosystem optimization	Evaluation of management alternatives before implementation	High data requirements and model complexity
Geographic Information Systems (GIS)	Spatial analysis of natural resources and agricultural landscapes	Biodiversity conservation, water regulation, landscape management	Supports resource planning and ecosystem-service mapping	Requires technical expertise and quality spatial datasets
Blockchain and Traceability Platforms	Secure recording of sustainability and environmental performance indicators	Ecosystem-service verification, carbon accounting	Transparency, traceability, sustainability certification	Limited adoption and implementation costs
Integrated Digital Regenerative Agriculture Platforms	Combination of AI, IoT, remote sensing, GIS, and DSS for ecosystem-based management	Soil health, biodiversity, carbon sequestration, water conservation, climate resilience	Holistic ecosystem monitoring and adaptive management	Lack of standardized frameworks and interoperability among technologies

performance become measurable and manageable objectives (Table 2). In this context, digitalization may represent the most significant evolution of conservation agriculture since its inception, providing a scalable pathway toward climate-resilient and ecosystem-service-centric food systems.

Challenges, Contradictions, and Future Directions

Despite increasing momentum, both Conservation Agriculture (CA) and Regenerative Agriculture

(RA) face unresolved scientific and implementation challenges. A fundamental limitation is the lack of a universally accepted definition of RA. Unlike CA, which is anchored in clearly defined management principles, RA encompasses a diverse and evolving set of practices, making cross-study comparisons and outcome assessments difficult (Newton *et al.* 2020; Giller *et al.* 2021). This conceptual ambiguity has hindered the development of standardized metrics and evidence-based policy frameworks.



Carbon sequestration remains another contentious issue. Although regenerative practices can enhance soil organic carbon stocks, sequestration rates vary widely across soils, climates, and management systems. Emerging evidence suggests that carbon gains may be context-dependent and insufficient, on their own, to offset agricultural greenhouse-gas emissions at meaningful scales (Amundson and Biardeau, 2018; Bossio *et al.* 2020). Consequently, regenerative agriculture should be viewed as a strategy for improving soil health and resilience rather than a universal climate solution.

Adoption barriers further constrain large-scale implementation. Competing uses of crop residues, socioeconomic limitations, labor requirements, and restricted access to knowledge, machinery, and financial incentives can reduce the feasibility of conservation and regenerative practices, particularly in smallholder systems (Giller *et al.* 2021; Sarkar *et al.* 2023). In parallel, the rapid commercialization of regenerative agriculture has raised concerns regarding “greenwashing,” whereby environmental claims often exceed measurable ecological outcomes. Future progress will depend on moving beyond practice-based classifications toward outcome-based evaluation frameworks that explicitly quantify ecosystem-service delivery, resilience, and socioeconomic outcomes (Storkey *et al.* 2024). Integrating ecosystem-service indicators with advances in artificial intelligence, remote sensing, digital soil monitoring, and monitoring–reporting–verification (MRV) systems offers a pathway for quantifying environmental performance at scale. Establishing standardized definitions, robust assessment protocols, and transparent reporting mechanisms will be essential to distinguish genuine ecosystem restoration from aspirational sustainability claims and to unlock the full potential of next-generation agricultural systems.

CONCLUSION

Sustainable agriculture is undergoing a fundamental transition from maximizing production to optimizing ecosystem functionality. Rather than representing competing paradigms, Conservation Agriculture (CA) and Regenerative Agriculture (RA) should be viewed as complementary approaches along a continuum of sustainable land stewardship. While CA provides a robust operational framework for

resource conservation, RA broadens the agenda toward ecosystem regeneration, resilience, and natural-capital restoration. A central message emerging from this review is that ecosystem services—including soil carbon sequestration, biodiversity conservation, water regulation, nutrient cycling, and pollination support—should serve as primary indicators of agricultural sustainability, replacing the traditional emphasis on yield alone. Simultaneously, advances in artificial intelligence, remote sensing, IoT-enabled monitoring, and digital soil assessment are creating unprecedented opportunities to quantify, monitor, and optimize these ecosystem outcomes. The convergence of conservation principles, regenerative practices, and digital technologies signals the emergence of a new paradigm: ecosystem-service-centric agriculture. Future food systems will be defined not only by their productivity, but by their capacity to restore ecological functions, enhance climate resilience, and sustain natural resources under increasing environmental pressures. Developing standardized metrics and scalable monitoring frameworks will be critical to translating this vision into measurable and actionable outcomes.

GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

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