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REGENERATIVE AGRICULTURE: CURRENT STATE, GOALS, AND FUTURE PERSPECTIVES

Marijana Jovanović Todorović[1*], Jonel Subić[1], Danijela Mirjanić[1], Marijana Joksimović[2]

[1]Institute of Agricultural Economics, Belgrade, Serbia,
[2]Alfa BK University, Faculty of Finance, Banking and Auditing, Belgrade, Serbia,
***Corresponding author: marijana_j@iep.bg.ac.rs**

Abstract: Regenerative agriculture has become a leading approach in transforming agrifood systems, focusing on restoring ecosystem functionality while preserving agricultural productivity. In contrast to sustainability-focused methods that typically prioritize reducing negative impacts, regenerative agriculture aims for net-beneficial results regarding soil vitality, biodiversity, climate stability, and economic resilience. Even with growing acceptance and policy attention, the notion is still variably defined, and empirical data are inconsistent. This paper integrates existing scientific literature to evaluate the condition of regenerative agriculture, its main objectives, recorded results, and future research and application viewpoints. We assess prevailing practices, environmental and socio-economic goals, along with methodological hurdles in assessing regenerative systems. We also highlight significant research gaps concerning metrics, scalability, and governance. The study finds that regenerative agriculture offers considerable promises for climate-resilient and multifunctional food systems; however, it needs standardized frameworks, extensive empirical research, and cohesive policy backing to evolve from an aspirational idea to a data-driven agricultural approach.

Keywords: Regenerative agriculture, Soil health, Agroecosystems, Sustainability transition, Ecosystem services

INTRODUCTION

During the second half of the 20th century, there was an intensification of agricultural production, which led to an increase in the yield of crops, but consequently caused negative effects on agricultural land, biodiversity, and stability of the agroecosystem (Pretty et al., 2018). According to estimates by the Food and Agriculture Organization of the United Nations (FAO, 2017), a significant loss (in %) of agricultural land worldwide shows signs of degradation, primarily due to erosion, loss of organic matter, and intensive use of chemical preparations (Blanco-Canqui et al., 2018). Approximately 25% of annually anthropogenic greenhouse gas (GHG) emissions, one-third of terrestrial acidification, and the majority of surface water eutrophication worldwide are currently caused by the global food system (Poore et al., 2018). The planet's carrying capacity will probably be exceeded if our food system keeps using fossil fuels, artificial fertilizers, synthetic pesticides, and food waste (Campbell et al., 2017). Thus, producing enough safe and nourishing food for an expanding and affluent population within the planet's carrying capacity is humanity's greatest problem (Willett et al., 2019).

Alternative agricultural paradigms have become more well-known in response to these difficulties. These include climate-smart agriculture, agroecology, organic farming, conservation agriculture, and, more recently, regenerative agriculture (RA). Because of its clear focus on improving resilience, restoring ecosystem function, and producing net-positive environmental results in addition to productive agricultural systems, RA has become one of the most talked-about frameworks among them (LaCanne et al., 2018; Schreefel et al., 2020).

Scientists, farmers, businesses, and legislators are increasingly promoting regenerative agriculture (RA) as a means of restoring ecosystem functioning while maintaining food security. Regenerative agriculture places more emphasis on the active regeneration of soil, biodiversity, and ecosystem services than traditional sustainability methods, which concentrate on reducing adverse effects (Rhodes, 2017; LaCanne and Lundgren, 2018; Lal, 2020). However, the term's quick spread has overtaken conceptual clarity and empirical support, sparking discussions about its practical applicability and scientific foundation.

Regenerative agriculture is most accurately characterized as a system grounded in principles, rather than merely a prescriptive compilation of practices. Fundamental principles frequently acknowledged in scholarly discourse encompass:

- Sustaining continuous soil cover to safeguard against erosion and foster soil microbiota (Thierfelder et al., 2021).
- Minimizing soil disturbance through reduced or no-tillage methodologies to preserve soil structure and carbon reserves (Lal, 2020).
- Maximizing biodiversity through the implementation of crop rotations, intercropping, and agroforestry practices to enhance ecosystem resilience and nutrient cycling (Kremen et al., 2012; Hartman et al., 2018).
- Incorporating livestock to emulate natural grazing behaviors, thereby recycling nutrients and augmenting soil health (Teague et al., 2016).
- Bolstering biological processes, encompassing soil microbial activity, pollination, and pest management (Schreefel et al., 2020).

These principles distinctly separate regenerative agriculture from conventional sustainability paradigms, which predominantly emphasize impact mitigation rather than proactive ecological regeneration (Doré et al., 2011; LaCanne et al, 2018).

MATERIAL AND METHODS

Historical Background

Regenerative agriculture draws from multiple disciplinary and practical traditions. Its conceptual foundations overlap with: Agroecology, emphasizing ecological processes, system-level thinking, and socio-cultural integration (Pretty, 2008; Gliessman, 2015); Conservation agriculture, which focuses on minimal soil disturbance, soil cover, and crop rotation (Thierfelder et al., 2021); Organic farming, particularly in its reduced reliance on synthetic inputs, although RA does not require certification (Gattinger et al., 2012). Holistic planned grazing, which model's livestock management on natural rangeland processes to restore soil and vegetation (Teague et al., 2016). Permaculture and regenerative design, emphasizing perennial systems, energy efficiency, and circular nutrient flows (Mollison, 1988; Stavi et al., 2015). The convergence of these disciplines reflects the interdisciplinary and context-specific nature of RA, making it adaptable but also challenging to standardize (Giller et al., 2021).

Goals and Objectives of Regenerative Agriculture

Soil Health Restoration - Enhancing soil quality is fundamental to Regenerative Agriculture (RA). Healthy soils deliver vital ecosystem services like nutrient cycling, water retention, and carbon sequestration. Techniques such as cover cropping, reduced tillage, and organic amendments boost soil organic matter, strengthen aggregate stability, and increase microbial diversity (Lal, 2020; Hartman et al., 2018; Pratt et al., 2020).

Climate Change Mitigation and Adaptation - Regenerative agriculture is increasingly viewed as a climate-smart strategy. RA methods can capture carbon in soils and biomass, lower nitrous oxide emissions, and build resilience against extreme weather like droughts and floods (Paustian et al., 2016; Mottet et al., 2017; Teague et al., 2016). Nonetheless, the potential for sequestration is highly specific, depending on baseline soil conditions, climate, and management intensity (Lal, 2020; Giller et al., 2021).

Biodiversity Enhancement - Boosting biological diversity serves both ecological and functional purposes. Diverse crop rotations, intercropping, agroforestry, and reduced chemical inputs aid soil organisms, pollinators, and natural pest predators (Kremen et. al., 2012; Schreefel et al., 2020). These biodiversity gains support ecosystem stability, resilience, and long-term productivity.

Socio-Economic Resilience - Regenerative agriculture can boost farmer livelihoods by cutting input costs, diversifying income sources, and reinforcing local food systems (Schader et al., 2018; LaCanne et al., 2018). Its participatory and adaptive nature prompts farmers to innovate and exchange knowledge, thereby enhancing social capital and community resilience (Chambers et al., 2013).

Current Adoption and Practice Diversity

RA adoption is on the rise, though unevenly distributed. Empirical studies reveal that uptake is highest in areas with established conservation agriculture programs, access to technical knowledge, and robust market or policy incentives (Giller et al., 2021; Thierfelder et al., 2021). Common practices include cover cropping, crop rotations, reduced tillage, organic amendments, holistic grazing, and agroforestry integration (Hartman et al., 2018; Schreefel et al., 2020). However, adoption is hindered by barriers such as Short-term yield trade-offs during transition phases (Thierfelder et al., 2021); labor and management complexity, and a lack of standardized monitoring and certification frameworks (Pratt et al., 2020; Reed et al., 2019).

Scientific Debates and Research Gaps

Despite growing popularity, RA faces critical scientific and operational debates: Conceptual clarity: The absence of a standardized definition allows flexibility but increases the risk of greenwashing (Giller et al., 2021). Evidence heterogeneity: Empirical outcomes vary depending on climate, soil type, and system design, complicating generalizations (Thierfelder et al., 2021; Mottet et al., 2017). Metrics and monitoring: There is a lack of harmonized indicators to assess soil health, biodiversity, carbon sequestration, and socio-economic impacts (Pratt et al., 2020; Schreefel et al., 2020). Scaling and policy integration: Moving from pilot studies to landscape-level adoption requires effective policy instruments, incentives, and risk-sharing mechanisms (Reed et al., 2019; Doré et al., 2011). Addressing these gaps requires long-term, systems-based research integrating ecological, agronomic, and socio-economic dimensions (Giller et al., 2021; Chambers et al., 2013; Pretty, 2008).

Current State of Regenerative Agriculture

Regenerative agriculture has been increasingly adopted globally over the past decade, with its uptake varying widely by region, crop type, and socioeconomic context. Evidence from North America, Europe, Australia, and parts of Latin America and Africa shows that RA is practiced across diverse systems, including row crops, pastures, orchards, and mixed farming systems (Giller et al., 2021; Thierfelder et al., 2021; LaCanne et al., 2018).

Regional Adoption Patterns

In North America, adoption is primarily driven by farmer-led initiatives, corporate sustainability programs, and climate-conscious markets. Key practices include cover cropping, no-tillage, integrated crop-livestock systems, and diversified rotations (LaCanne et al., 2018; Teague et al., 2016). In Europe, RA adoption is often integrated with agroecological and organic systems, emphasizing soil organic matter enhancement and biodiversity conservation. Policy incentives, such as agri-environmental schemes, have facilitated the adoption of practices (Doré et al., 2011; Schreefel et al., 2020). In Australia and New Zealand, holistic grazing and perennial pastures dominate, focusing on soil restoration and resilience in semi-arid rangelands (Teague et al., 2016; Mottet et al., 2017). In Africa and Latin America, adoption is emerging in smallholder systems, often linked to food security and climate adaptation initiatives. Practices include agroforestry, intercropping, and soil fertility management with organic inputs (Pretty, 2008; Giller et al., 2021).

Dominant Practices and Management Strategies

There are common regenerative practices identified in the literature: using cover cropping and green manures - enhancing soil fertility, reducing erosion, and increasing microbial activity (Thierfelder et al., 2021; Pratt et al., 2020). Practices with reduced or no-tillage preserve soil structure, reduce compaction, and increase carbon sequestration (Lal, 2020). Diverse crop rotations and intercropping lead to increasing nutrient use efficiency and resilience to pests and diseases (Hartman et al., 2018; Kremen et al., 2012). Agroforestry and perennial integration - stabilize soil, improve microclimate regulation, and sequester carbon (Schreefel et al., 2020; Stavi et al., 2015). Holistic livestock grazing: Improves nutrient cycling, reduces invasive species, and enhances pasture productivity (Teague et al., 2016). Organic amendments: Compost, manure, and biochar are applied to restore soil fertility and microbial communities (Lal, 2020; Gattinger et al., 2012).

Measured Outcomes

Empirical studies indicate that regenerative agriculture can deliver measurable ecological and socioeconomic outcomes, although results vary:

- Soil health: Soil organic carbon increases by 0.3-1.2 Mg C ha^{-1} yr^{-1} under regenerative practices, depending on soil type, climate, and implementation duration (Paustian et al., 2016; Lal, 2020).
- Water retention and infiltration: No-till and cover-cropping systems can increase water infiltration by 20-50%, improving drought resilience (Thierfelder et al., 2021).
- Biodiversity: Plant and soil microbial diversity are enhanced, leading to improved pollination, pest regulation, and nutrient cycling (Kremen et al., 2012; Hartman et al., 2018).
- Yield and productivity: Many studies report comparable or slightly reduced short-term yields during the transition period, followed by long-term stabilization or improvement (Giller et al., 2021; LaCanne et al., 2018).
- Socioeconomic outcomes: Reduced input costs, diversified income sources, and improved farm resilience have been documented, especially when supported by market or policy incentives (Schader et al., 2018; Chambers et al., 2013).

Challenges in Current Adoption

Despite its potential, RA adoption faces significant barriers, including knowledge gaps. A lack of region-specific knowledge and training can hinder adoption (Pretty, 2008; Schreefel et al., 2020). Measurement inconsistencies, particularly variability in how soil health, biodiversity, and ecosystem services are measured, make cross-study comparisons difficult (Pratt et al., 2020). Economic trade-offs: Initial yield reductions and labor requirements can deter adoption, particularly for smallholder farmers (Thierfelder et al., 2021). Policy and market limitations: Absence of standard certification frameworks and limited financial incentives reduce scalability (Reed et al., 2019).

Future Perspectives and Research Directions

A critical future step is harmonizing definitions and metrics to allow consistent monitoring, assessment, and comparison. Multi-dimensional frameworks combining soil health, biodiversity, carbon sequestration, water retention, and socio-economic resilience are required (Pratt et al., 2020; Schreefel et al., 2020). Metrics should be scalable, applicable from field to landscape levels, and sensitive enough to detect short- and long-term changes.

Most empirical studies on RA are short-term (<5 years) and geographically limited. Long-term, multi-site research can clarify the temporal dynamics of soil carbon accumulation (Paustian et al., 2016). Also, can determine resilience to climate extremes (Mottet et al., 2017) and evaluate trade-offs between productivity and ecosystem services (Giller et al., 2021).

Policy frameworks can accelerate RA adoption through payments for ecosystem services, carbon credit schemes, and subsidies for regenerative practices. Evidence-based policy requires robust monitoring, evaluation, and reporting systems (Reed et al., 2019; Doré et al., 2011).

Emerging technologies can enhance regenerative agriculture by remote sensing and drones for monitoring soil health, crop diversity, and vegetation cover (Hartman et al., 2018). Also, it can be used as the decision-support tools for adaptive management based on real-time soil, weather, and crop data (Stavi and Lal, 2015). Data-driven can be used for giving insights for carbon accounting, biodiversity assessment, and landscape-level planning in future (Paustian et al., 2016).

Future perspectives for social and knowledge systems, it can be significantly improved by regenerative agriculture. Farmer-led innovation, co-creation of knowledge, and participatory research are essential to tailor regenerative agriculture to local contexts. Social learning networks and knowledge-sharing platforms can increase adoption, reduce risks, and foster innovation (Chambers et al., 2013; Pretty, 2008).

RESULTS AND DISCUSSION

Regenerative agriculture represents a paradigm shift from conventional or even sustainability-focused farming, emphasizing restoration rather than mere impact reduction. The synthesis of current literature shows that RA can deliver measurable ecological benefits, including improved soil health, enhanced biodiversity, and increased water retention (Lal, 2020; Hartman et al., 2018; Kremen et al., 2012). At the same time, it can support socio-economic outcomes such as diversified income, reduced dependence on chemical inputs, and long-term farm resilience (LaCanne et al., 2018; Schader et al., 2018).

Despite these promising outcomes, several critical challenges remain. First, adoption is uneven globally and context-specific, influenced by climate, soil conditions, market access, labor availability, and policy frameworks (Giller et al., 2021; Thierfelder et al., 2021). Second, the lack of a standardized definition and monitoring framework has led to conceptual ambiguity and the risk of "greenwashing" (Schreefel et al., 2020). Third, long-term, multi-site empirical evidence remains limited, making it difficult to fully quantify trade-offs between productivity and ecological gains (Paustian et al., 2016; Mottet et al., 2017).

The literature suggests that RA should not be viewed as a prescriptive set of practices but rather as a principle-driven, adaptive framework. Its integration with broader sustainability and climate-smart agricultural strategies can enhance both resilience and productivity. Policy support, knowledge co-creation, and technological innovation are essential to scale RA beyond pilot sites and early adopters. For example, digital decision-support tools, remote sensing for soil and vegetation monitoring, and farmer participatory networks can accelerate adoption and improve outcome monitoring (Hartman et al., 2018; Stavi et al., 2015).

Finally, the research community must prioritize system-level studies that link soil health, biodiversity, climate mitigation, and socio-economic outcomes. This requires interdisciplinary collaboration across agronomy, ecology, economics, and social sciences.

By establishing robust evidence, RA can move from an aspirational framework to an evidence-based strategy that contributes meaningfully to sustainable food systems.

CONCLUSION

Regenerative agriculture offers a compelling pathway to transform agricultural systems toward ecological and socio-economic sustainability. Its principle-based framework centered on soil health, biodiversity, climate resilience, and farmer well-being addresses multiple dimensions of agricultural sustainability simultaneously. Current evidence shows that RA practices can enhance soil organic carbon, microbial diversity, water retention, and landscape multifunctionality, although outcomes are highly context dependent. Future adoption and scaling will require: Standardized definitions and metrics for consistent evaluation. Long-term, multi-site research to quantify ecological and socio-economic outcomes. Policy frameworks and market incentives to reduce adoption barriers and encourage ecosystem service provision. Technological and social innovations to support adaptive management and farmer knowledge networks. With these components, regenerative agriculture can evolve from a conceptually promising framework into a scientifically grounded and practically viable approach for sustainable, climate-resilient, and profitable food systems.

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