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Integrated assessment of environmental risks during regenerative farming implementation on degraded soils: A methodological review

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Abstract

This study systematically assesses soil degradation and environmental risks arising from agroecosystem transformation during the transition from intensive to regenerative agriculture. Amid climate change and declining fertility, regenerative practices effectively enhance soil organic carbon sequestration and stimulate microbial activity. However, the conversion phase involves non-linear, asymmetric restructuring of biogeochemical cycles, which can destabilize labile carbon pools and mobilize reactive soil compounds. The aim of this study was to develop a conceptual and methodological framework for the integrated evaluation of these multi-directional shifts. We propose the Regenerative Transition Safety Index (RTSI), which integrates three core domains: the Biological Functionality Index (BFI), the Carbon Stability Index (CSI), and the Ecotoxicological Load Index (ETI). Within this risk-sensitive module, positive contributions of microbial biomass, soil respiration, and enzymatic activity are balanced against negative pressures such as ionic stress, nitrogen imbalances, and heavy metal bioavailability in the rhizosphere. A five-level graded interpretation scale for the RTSI was established, defining threshold intervals based on the stability boundaries of soil ecosystems and the concept of the adaptive cycle. RTSI enables early detection of hidden ecological risks before irreversible changes occur, ensuring proactive management and long-term soil health during agroecosystem transformation.

Keywords: *regenerative agriculture, environmental risks, soil health, integrated index, degraded soils, agroecosystems, ecological stability.*

Introduction

The need to reconsider conventional land-use systems in favor of regenerative agriculture is driven by rapid changes in the agricultural sector, ranging from global climate change to accelerating soil degradation. The strategic importance of this transition lies in its potential to contribute to the achievement of the Sustainable Development Goals through enhanced carbon sequestration, restoration of soil resources, and increased adaptive capacity of agroecosystems (Sher et al., 2024; Saleem et al., 2025). In global practice, regenerative approaches include the use of cover crops, green manures, organic amendments, bio-based inputs, and reduced (mini-till) or zero tillage (no-till) systems (Newton et al., 2020). Most studies focus on positive trends in individual indicators, such as soil organic carbon (SOC), biological activity, and agroecosystem productivity (Blanco-Canqui and Ruis, 2020). However, recent reviews highlight substantial spatial and temporal variability in outcomes, emphasizing the strong dependence of soil recovery processes on local soil-climatic conditions and the duration of regenerative practices (Khangura et al., 2023). Particular attention should be paid to the ecological neutrality of this transition in degraded soils, which are often characterized by disrupted trophic structure, low buffering capacity, and the accumulation of chemical pollutants. In such systems,

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the intensification of biological processes cannot be considered inherently safe. It is accompanied by a restructuring of soil microbial communities and shifts in organic matter mineralization pathways, creating conditions for latent environmental risks. For instance, intensification of agricultural practices may reduce the complexity of microbial interaction networks, including key functional groups such as arbuscular mycorrhizal fungi (Banerjee et al., 2019). Additionally, the biological intensification of agro-technologies, such as recycling organic wastes or applying biopesticides, may introduce new contaminants or negatively affect non-target microbial communities (Vermeire et al., 2024). The accumulation of potentially toxic elements and the spread of antibiotic resistance genes under prolonged organic amendments further highlight the need for ecotoxicological assessment (Khan et al., 2021). During transitional phases, increased biological activity is often associated with dynamic instability, including fluctuations in dissolved organic carbon. The accumulation of labile organic compounds and low-molecular-weight organic acids in the rhizosphere can alter metal speciation, increasing their bioavailability and mobility (Zhao et al., 2025, 2026), thereby intensifying ecotoxicological risks in previously contaminated soils. Therefore, the assessment of regenerative practices should integrate not only carbon sequestration but also the geochemical dynamics of toxic elements and structural transformations of soil biota (Telo da Gama, 2023).The aim of this study is to develop a conceptual framework and integrated indicators for assessing environmental risks arising during agroecosystem transformation under regenerative restoration of degraded soils. To achieve this aim, the following objectives were defined: to analyze current scientific approaches to the impact of regenerative practices on degraded soils; to identify and classify key environmental risks (chemical, biological, and physical) during the transition period; to substantiate a system of structural, functional, and ecotoxicological indicators for comprehensive risk assessment; and to develop a conceptual model and algorithms for risk mitigation under regenerative management.

Methodological framework of the literature screening

The methodological framework of this study is based on an integrated systems analysis that combines physicochemical, biological, and ecotoxicological parameters into a unified diagnostic system for identifying environmental risks associated with soil transformation during the regenerative agricultural transition. The collection and systematization of empirical data to construct the safety index indicators relied on a structured screening of peer-reviewed scientific publications indexed in Scopus and Web of Science databases for the period 2010–2025 (Khangura et al., 2023; Sher et al., 2024). The analytical literature search was systematically executed using targeted keyword combinations, including “regenerative agriculture,” “soil health,” “carbon sequestration,” “soil structure,” “microbial biomass,” “carbon use efficiency,” “heavy metals,” and “soil ecotoxicology” (Newton et al., 2020; Vermeire et al., 2024). The selection criteria for the scrutinized studies required the presence of quantitative data regarding structural, functional, or ecotoxicological changes in transitional agroecosystems, ensuring that the final framework reflects ecologically relevant and highly sensitive responses to anthropogenic pressure. The ultimate construction of the proposed conceptual model and its quantitative scale involved three sequential analytical phases. First, a comprehensive reference database of quantitative indicators was compiled from the extracted international literature. Second, data standardization and normalization procedures were formalized to project diverse units onto a unified dimensionless scale ranging from 0 to 1 (Makovníková et al., 2024). This normalization was designed as a direct function for stabilizing ecological parameters and an inverse function for risk-oriented parameters to properly account for their specific role in soil dynamics. Third, an additive mathematical framework based on multifactor analysis and ecological vulnerability functions was developed, allowing the calculation of an integrated transition index that directly quantifies the ecological balance between restorative trends and hidden degradation processes during agroecosystem restructuring.

Results and discussion

Conceptual development of the environmental risk assessment framework

A three-component conceptual model was established to provide a comprehensive evaluation of environmental risks during the conversion from conventional to regenerative agroecosystems, adapting a systems approach that views soil as an integrated adaptive matrix where physical, biological, and chemical components interact nonlinearly (Lehmann et al., 2020). The integration of structural, functional, and ecotoxicological parameters within a singular framework transforms

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fragmented analytical observations into an organized diagnostic system capable of capturing latent soil degradation processes. The blueprint of this multi-metric approach is visualized in the dynamic interlinks forming the comprehensive safety framework (Fig. 1). As illustrated in the conceptual diagram, the index matrix coordinates independent environmental blocks to characterize dynamic degradation levels during the land-use conversion phase.

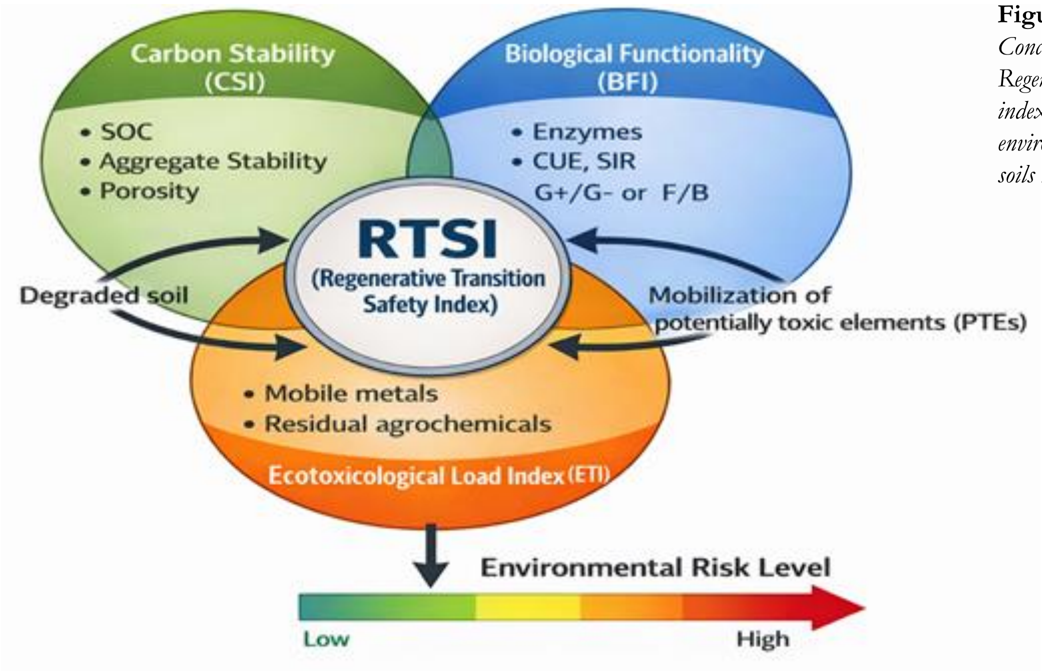

Figure 1
Conceptual framework of the Regenerative transition safety index (RTSI) for assessing environmental risks in degraded soils under regenerative agriculture

The structural component of the model establishes the physical basis of soil ecosystem stability, determining its resistance to erosion, compaction, pore space degradation, and organic matter loss (Blanco-Canqui and Ruis, 2020). Even under increasing soil organic carbon (SOC) levels, unbalanced management may exacerbate structural instability (Demydenko & Zadubynna, 2024). Soil pore architecture regulates gas exchange and the formation of anaerobic microsites, and any disruption of this balance through compaction can trigger rapid redox transformations, fundamentally altering the direction of biogeochemical cycles (Pessoa et al., 2023). Within this analytical framework, key physical parameters are analyzed as primary indicators of instability, reflecting specific risks associated with the dominance of labile organic matter fractions, macroaggregate breakdown, and structural failure of the soil water-air regime, as detailed in Table 1. Capillary porosity and soil pore architecture are key determinants of advective-diffusive transport of water, gases, and dissolved substances, directly regulating the hydrological regime and gas exchange intensity (Pessoa et al., 2023). Pore structure controls not only water retention but also oxygen and CO_2 diffusion, root and microbial aeration, and the spatial distribution of anaerobic microsites. Since oxygen availability is limited by the fraction of air-filled pores, disturbances caused by compaction or waterlogging can trigger redox tran-

Table 1. *Structural indicators as proxies of environmental risks of soil degradation*

Indicator	Ecological significance	Potential environmental risks during the transition period
Soil organic carbon (SOC) content	Energy base of the soil system	Dominance of labile fractions; accelerated mineralization; instability of carbon sequestration; increased CO_2 emissions
Aggregate stability	Protection against erosion and stabilization of SOC	Breakdown of macroaggregates; release of physically protected carbon; increased erosion vulnerability
Capillary porosity	Gas exchange, redox regime, and water infiltration	Soil compaction and anaerobization; enhanced denitrification and increased N_2O emissions

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sformations, altering the direction of biogeochemical cycles (Xu et al., 2025). Within the proposed framework, structural indicators are interpreted as predictors of ecosystem instability, reflecting risks associated with the dominance of labile organic matter fractions, reduced aggregate stability, and dysfunction of the soil water-air regime (Blanco-Canqui and Ruis, 2020; Zhao et al., 2026). The functional component of the model characterizes the intensity and direction of metabolic processes governing organic matter transformation, nutrient cycling, and trophic network structure (Philippot et al., 2024). Recent studies emphasize that increased biological activity during the transition period is not a universal indicator of stability, particularly in anthropogenically degraded soils (Bastida et al.,2021). Long-term observations show that the combined effects of reduced tillage and external organic inputs lead to substantial restructuring of soil microbial communities (Dunn et al.,2025; Okur et al.,2026). High inputs of labile substrates, as reflected by substrate-induced respiration (SIR), promote the dominance of copiotrophic (r-strategist) microorganisms (Steinberger et al., 2024). While this indicates strong microbial responsiveness to resource availability, it is often associated with destabilization of biogeochemical processes. Within this model, functional indicators are interpreted through the lens of ecological risk, including simplification of microbial community structure, metabolic imbalance between syn thesis and mineralization, and accelerated carbon turnover, which are systematically categorized in Table 2.

Table 2. *Functional indicators of soil biota as proxies of environmental risks of soil degradation*

Indicator	Ecological significance	Potential environmental risks during the transition period
Soil enzymatic activity	Intensity of biochemical processes of organic matter transformation and nutrient mobilization	Imbalance between synthesis and mineralization; dominance of catabolic processes; instability of biogeochemical cycles
Microbial biomass carbon (MBC)	Size of the active biological pool and microbial transformation potential	Dominance of fast-growing (copiotrophic) groups; reduced long-term carbon sequestration efficiency
Basal respiration	Intensity of background mineralization of organic carbon	Accelerated loss of labile carbon; reduced sequestration efficiency
Substrate-induced respiration (SIR)	Potential for microbial metabolic activation in response to labile carbon inputs	Activation of r-strategist (copiotrophic) groups; short-term mineralization pulses; functional instability
Microbial carbon use efficiency (CUE)	Fraction of carbon incorporated into biomass rather than mineralized to CO_2	Low CUE → dominance of mineralization over humification; reduced long-term carbon stabilization
Fungal-to-bacterial ratio	Structural and functional organization of microbial transformation pathways	Shift toward bacterial dominance; reduced carbon stabilization; simplification of trophic structure

Microbial carbon use efficiency (CUE) is a key parameter describing the balance between carbon assimilation into biomass and its mineralization to CO_2 (Dang et al., 2024). It is highly sensitive to substrate quality, nutrient status, pH, and hydrothermal conditions (Li and Qi, 2025). Low CUE values in transitional agroecosystems indicate energetic inefficiency and a shift toward decomposition-dominated processes, which leads to short-term pulses in functional molecular diversity without long-term structural humification (Davenport et al., 2025). The ecotoxicological component is aimed at identifying latent and delayed environmental risks that may intensify under increased biological activity in soils (Khan et al., 2021). Elevated concentrations of dissolved organic carbon and organic acids in the rhizosphere can mobilize heavy metals and residual xenobiotics, increasing their bioavailability and toxicity (Kicińska et al., 2022). The bioavailability of heavy metals is governed by their speciation, complexation, and physicochemical conditions of the soil environment, including pH, redox potential, and organic carbon content (Lishchuk et al., 2023; Rafie-Rad et al., 2025). Increased proportions of mobile forms of copper, zinc, cadmium, and lead enhance ecotoxicological risks for soil biota and facilitate their transfer into trophic chains (Kicińska et al., 2022). Persistent synthetic pesticides may remain in soils for extended periods, creating chronic toxicological pressure on soil organisms (Daraban et al., 2023; Lishchuk et al., 2024). These compounds affect non-target organisms, including microorganisms, and exert selective pressure that can lead to the development of resistant popula-

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tions (Vermeire et al., 2024). The critical parameters and environmental threats monitored under this chemical component are presented in Table 3. The integration of structural, functional, and ecotoxicological components within a unified conceptual framework enables a comprehensive assessment of environmental risks of soil degradation during the transition period. This approach provides a methodological basis for developing an integrated transition index aimed not only at evaluating regeneration outcomes but also at assessing the environmental safety of agroecosystem transformation.

Table 3. *Ecotoxicological indicators of environmental risks of soil degradation*

Indicator	Ecological significance	Potential environmental risks during the transition period
Mobile forms of Cu, Zn, Cd, Pb	Chelation processes, application of organic and mineral fertilizers, accumulation due to previous agricultural practices	Toxicity to soil biota; inhibition of enzymatic activity; disruption of microbial community structure; risk of trophic transfer
Residual pesticides	Agro-technological pressure and accumulation of persistent compounds	Long-term contamination; suppression of soil biota; selective pressure and development of resistance; reduced biodiversity
Source: ***own elaboration.***		

Formulation and scaling of the Regenerative Transition Safety Index (RTSI)

To integrate multidirectional structural, functional, and ecotoxicological changes in soil ecosystems during the transition from intensive to regenerative agriculture, the Regenerative Transition Safety Index (RTSI) was developed. This index is designed to quantitatively assess the environmental safety of transformation processes and reflects the dynamic balance between the restoration of soil functional integrity and the emergence of new environmental risks. Methodologically, the proposed approach aligns with contemporary soil health assessment frameworks, which emphasize the integration of multiple indicators into a single index for quantitative evaluation and comparison of soil ecosystem conditions (Lehmann et al., 2020; Makovníková et al., 2024). Conceptually, RTSI is based on the definition of soil health as the capacity of soil to function as a living ecosystem and sustain ecosystem services under anthropogenic pressure (Lehmann et al., 2020). Soil is considered a multifunctional ecosystem that regulates water balance, biogeochemical cycles, and carbon sequestration, while being continuously exposed to anthropogenic and climatic pressures (Telo da Gama, 2023). Therefore, its assessment requires a systems approach, as improvements in individual parameters do not necessarily indicate increased ecosystem stability. Thus, RTSI is not intended to measure the "outcome of regeneration" but rather to evaluate the environmental safety of the transition trajectory. Accordingly, it is necessary to formalize the index structure and define an algorithm for integrating indicators that quantitatively reflects the balance between restorative and risk-generating processes in soil ecosystems. The integrated index consists of three component indices: biological functionality, carbon stability, and ecotoxicological load. The Regenerative Transition Safety Index (RTSI) is calculated as an additive index integrating three component indicators according to Equation [1]:

$$RTSI = \frac{BFI + CSI + ETI}{3} \qquad [1]$$

where: BFI – biological functionality index; CSI – carbon stability index; ETI – ecotoxicological load index.

All component indices are normalized to a 0–1 scale prior to integration. Positive contributions of biological functionality (BFI) and carbon stability (CSI) are balanced against the negative effect of ecotoxicological load (ETI), reflecting its risk-generating nature. Higher RTSI values indicate the predominance of restorative processes, whereas lower values reflect increasing environmental risk. The specific criteria, operational directions, and index weights assigned to each distinct parameter within the integrated framework are synthesized in Table 4. The biological functionality index (BFI) reflects the ability of the soil biota to sustain key ecosystem functions, including organic matter transformation, nutrient cycling, and stabilization of trophic interactions (Philippot et al., 2024). It integrates indicators such as microbial biomass, soil respiration, and enzymatic activity as sensitive proxies of soil functional status (Dunn et al., 2025; Okur et al., 2026). Importan-

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Table 4. *System of indicators and evaluation criteria for the Regenerative Transition Safety Index (RTSI)*

Index component	Indicator (criterion)	Target direction (optimum)	Effect on the index
Biological functionality	Microbial biomass (C_{mic}, mg kg^{-1} soil)	Increase toward ecological optimum	Stimulating
	Basal respiration (R_{bas}, mg CO_2–C kg^{-1} day^{-1})	Stabilization (metabolic balance)	Stimulating
	Soil enzymatic activity (EA, rel. units)	Increase within functional equilibrium	Stimulating
Carbon stability	Soil organic carbon (SOC, %, g kg^{-1})	Stable increase	Stimulating
	Stable organic carbon fractions (SOC_{stable}, g kg^{-1})	Increase in stabilized carbon pool	Stimulating
	Aggregate stability (%)	Improvement of soil structure	Stimulating
Ecotoxicological load	Electrical conductivity (EC, dS m^{-1})	Reduction to background levels	Destimulating
	Nitrate nitrogen (NO_3–N, mg kg^{-1})	Minimization of excess accumulation	Destimulating
	Mobile forms of heavy metals (Cu, Zn, Cd, Pb, mg kg^{-1})	Reduction of mobility and bioavailability	Destimulating

Note: Stimulating – indicators increase the index value, while destimulating – indicators decrease it and are included as risk-related parameters. Source: own elaboration.

tly, microbial activity intensity is not a direct indicator of carbon accumulation or stabilization efficiency (Bastida et al., 2021). The balance between respiration and biomass growth is governed by microbial carbon use efficiency (CUE), which depends on microbial community composition and abiotic conditions (Dang et al., 2024; Li and Qi, 2025). Therefore, increased “overall activity” in regenerative systems may exhibit asymmetric effects. Within this framework, high BFI values indicate coordinated and functionally efficient biological activity rather than merely accelerated mineralization processes. The Carbon Stability Index (CSI) characterizes both the accumulation and persistence of soil organic carbon under transitional and potentially unstable conditions (Yadav et al., 2024). Unlike conventional approaches that rely on total organic carbon as a universal indicator, CSI accounts for the structure of carbon pools (labile and stable fractions), their physical protection within soil aggregates, and their interaction with microbial metabolism (Murindangabo et al., 2023; Zhao et al., 2026). This allows differentiation between short-term increases in carbon turnover and long-term carbon stabilization (Davenport et al., 2025). The proposed approach is consistent with recent methodologies that integrate fractionation, lability, and aggregate protection into carbon stability assessment (Yadav et al., 2024). The ecotoxicological load index (ETI) reflects latent environmental risks that may arise in agroecosystems during regenerative transition, even under positive trends in biological and carbon-related indicators (Vermeire et al., 2024). Conceptually, ETI is based on the premise that environmental safety depends not only on organic matter accumulation or increased biological activity but also on the stability of physicochemical conditions controlling the mobility, bioavailability, and toxicity of elements in soil (Khan et al., 2021). The mobility and bioavailability of metals and metalloids are controlled by their interactions with the mineral and organic soil matrix, including sorption–desorption processes, complexation, redox reactions, and precipitation–dissolution equilibria (Rafie-Rad et al., 2025). Key regulating factors include soil pH, ionic strength of the soil solution, and the composition of the sorption complex (Kicińska et al., 2022). Thus, changes in soil acidity or ionic composition may significantly alter environmental risk without changes in total element concentrations (Lishchuk et al., 2023). Experimental evidence indicates that even moderate soil acidification can substantially increase the mobility of metals such as cadmium and zinc, while soil buffering capacity determines the extent of their bioavailability (Kicińska et al., 2022). This demonstrates that ecotoxicological risk depends not only on element concentrations but also on soil physicochemical conditions (Zhao et al., 2025). An additional component of ecotoxicological load is

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nitrogen imbalance. Elevated nitrogen inputs, even within agronomically acceptable ranges (95–120 kg N ha^{-1}), may pose a moderate risk of nitrate leaching into groundwater. More intensive fertilization (150–180 kg N ha^{-1}) requires optimization to maintain acceptable environmental risk levels (Duda et al., 2023). Therefore, increased productivity or biological activity does not preclude latent risks of nitrate migration within the soil-groundwater system, necessitating inclusion of this parameter in the ecotoxicological sub-index (Duda et al., 2023). Accordingly, the ecotoxicological load index (ETI) integrates indicators reflecting potential environmental threats, including electrical conductivity (as an indicator of ionic stress), nitrate nitrogen content (as a marker of nitrogen imbalance and leaching risk), and mobile forms of Cu, Zn, Cd, and Pb (as indicators of element mobilization) (Khan et al., 2021; Lishchuk et al., 2023). This approach enables identification of situations where regenerative transition is associated with temporary improvements in biological or carbon-related parameters alongside destabilization of soil physico-chemical conditions, increasing ecotoxicological risk (Vermeire et al., 2024). Persistent synthetic pesticides may remain in soils for extended periods, creating chronic toxicological pressure on soil organisms (Daraban et al., 2023; Lishchuk et al., 2024), while adaptive management becomes crucial during land conversion (Eslami, 2025; Ofosu et al., 2023). Within the overall RTSI framework, ETI functions as a risk-sensitive module complementing biological functionality and carbon stability indicators, ensuring a comprehensive assessment of environmental safety in agroecosystems. To ensure analytical robustness and applicability for monitoring purposes, a graded inter-pretation scale for the Regenerative Transition Safety Index (RTSI) was established based on the dynamic ba-lance between stabilizing and destabilizing processes, providing five operational categories as set out in Table 5.

Table 5. *Threshold intervals and ecological interpretation of the Regenerative transition safety index (RTSI)*

Index value	Environmental safety category	Level of environmental risk manifestation
0.75–1.00	Environmentally safe transition	Dominance of restorative processes; minimal risks
0.60–0.74	Managed transition	Predominance of recovery with controlled risks
0.45–0.59	Unstable transition	Imbalanced state between recovery and risk
0.31–0.44	Risk-prone transition	Partial offset of positive changes by risk factors
< 0.30	Environmentally hazardous state	Dominance of destabilization processes

Source: own elaboration.

Since the index integrates both positive components (biological functionality and carbon stability) and a negative component (ecotoxicological load), its value reflects the balance between restorative processes and environmental risks. Values close to 0.5 indicate a state of dynamic equilibrium between stabilizing and destabilizing processes. Values above 0.75 reflect a stable dominance of restorative processes, whereas values below 0.30 indicate systemic destabilization of the soil ecosystem. A five-level environmental safety scale was applied for RTSI interpretation. Threshold intervals (0.75, 0.60, 0.45, 0.30) were defined based on reported stability boundaries of soil ecosystems and the concept of the adaptive cycle, which describes phase transitions in complex systems. Within this framework, values of 0.75–1.00 correspond to a stabilized system characterrized by structural and functional consolidation and low environmental risk. The range of 0.60–0.74 reflects a managed transition with maintained resilience and moderate biogeochemical stress. Values of 0.45–0.59 indicate an unstable transition, where the balance between recovery and risk is fragile. The interval of 0.31–0.44 represents a risk-prone transition associated with increasing destabilization. Values below 0.30 indicate an environmentally hazardous state dominated by degradation processes. These thresholds do not represent regulatory limits for individual indicators but serve as integrative ranges for assessing the phase state of agroecosystems during regenerative transformation.

RTSI should therefore be interpreted not as a static measure of soil condition but as an indicator of dynamic ecological balance under regenerative transition. Its application enables: identification of critical transition phases where biological activation is accompanied by increased risks; comparison of management practices in terms of environmental safety; early detection of risks prior to irreversible changes, such as loss of stable carbon pools or disruption of soil biota; and support for adaptive management decisions during regenerative transformation. Thus, the Regenerative transition safety index (RTSI) represents a risk-sensitive tool for assessing agroecosystem transformation, enabling timely identification of soil degradation risks and supporting environmentally safe land-use practices. This approach

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aligns with contemporary interpretations of soil health as a foundation for sustaining ecosystem functions and ensuring sustainable land management (Lehmann et al., 2020; Telo da Gama, 2023).

Conclusions

This review demonstrates that the transition from conventional intensive practices to regenerative agriculture represents a complex, non-linear transformation process accompanied not only by the gradual restoration of soil biological functions but also by the simultaneous emergence of latent environmental risks. Synthesis of recent scientific literature indicates that increased microbial activity during the conversion phase routinely exhibits asymmetric dynamics, potentially leading to the destabilization of unstable carbon pools and the mobilization of reactive soil compounds. The analytical findings confirm that reliance solely on total soil organic carbon content is insufficient for capturing the true ecological stability of degraded soils. Instead, a comprehensive evaluation must integrate functional biological traits and ecotoxicological metrics capable of isolating trophic network restructuring, carbon fraction volatility, and shifts in the bioavailability of potentially toxic elements in the rhizosphere. The established conceptual framework addresses this diagnostic gap by systematically coordinating three core domains: the biological functionality index, the carbon stability index, and the ecotoxicological load index. This integrated matrix enables researchers and land managers to distinguish between genuine, long-term soil ecosystem recovery and short-term metabolic pulses driven by accelerated mineralization pathways. Based on this structural framework, the Regenerative Transition Safety Index (RTSI) is introduced as a robust conceptual and methodological tool designed to evaluate the dynamic balance between restorative shifts and hidden degradation factors. The integration of highly sensitive criteria, such as microbial biomass carbon, substrate-induced respiration, aggregate stability, and heavy metal mobility, provides a comprehensive foundations for the early identification, risk mapping, and proactive adaptive management of agroecosystems undergoing regenerative transformation.

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