LANDSCAPE ECOLOGY AND RESILIENCE OF AGROECOLOGICAL YIELDS: A GLOBAL SYNTHESIS ON ECOSYSTEM SERVICE STABILITY AND FOOD SECURITY

ECOLOGIA DE PAISAGENS E RESILIÊNCIA DA PRODUTIVIDADE AGROECOLÓGICA: UMA SÍNTESE GLOBAL SOBRE A ESTABILIDADE DE SERVIÇOS ECOSSISTÊMICOS E A SEGURANÇA ALIMENTAR

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Abstract
Agricultural production systems increasingly face ecological instability driven by biodiversity loss, landscape simplification, and climate variability. While a growing body of research has examined the role of ecosystem services in supporting agricultural productivity, most studies have focused on average yield performance rather than the temporal stability of production across heterogeneous landscapes. This gap limits the understanding of how spatial landscape structure influences the resilience of agroecosystems and their capacity to sustain food production under environmental uncertainty. The main objective of this study was to synthesize global evidence on how landscape configuration influences the stability of ecosystem services and the resilience of agroecological yields. Methodologically, this study employed an integrative literature review conducted between November 2025 and February 2026 across major

Resumo
Os sistemas de produção agrícola enfrentam crescente instabilidade ecológica associada à perda de biodiversidade, à simplificação das paisagens agrícolas e à intensificação das mudanças climáticas. Embora um número crescente de estudos investigue o papel dos serviços ecossistêmicos no suporte à produção agrícola, a maior parte dessas pesquisas concentra-se na produtividade média, negligenciando a estabilidade temporal da produção em paisagens heterogêneas. Essa lacuna limita a compreensão de como a estrutura espacial das paisagens influencia a resiliência dos agroecossistemas e sua capacidade de sustentar a produção de alimentos diante de incertezas ambientais. O objetivo principal deste estudo foi sintetizar evidências globais sobre como a configuração da paisagem influencia a estabilidade dos serviços ecossistêmicos e a resiliência da

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scientific databases. An initial set of 216 records was identified and subjected to systematic screening procedures based on explicit inclusion and exclusion criteria, resulting in a final analytical corpus of 25 studies addressing interactions between landscape structure, biodiversity, and agricultural productivity. The results indicate that landscape heterogeneity, habitat connectivity, and the presence of semi-natural habitats significantly enhance ecosystem service provision, particularly pollination and biological pest control. These ecological processes contribute not only to increased crop productivity but also to greater yield stability across environmental fluctuations. The findings suggest that agricultural resilience is strongly influenced by the ecological structure of landscapes rather than by input-intensive production strategies alone. In conclusion, designing biodiversity-rich agricultural landscapes emerges as a key strategy for stabilizing ecosystem services and strengthening the resilience of food production systems in the context of global environmental change.

Keywords: Ecosystem Services. Agricultural Biodiversity. Landscape Connectivity. Yield Stability. Sustainable Agriculture.

produtividade agroecológica. Metodologicamente, foi realizada uma revisão integrativa da literatura conduzida entre novembro de 2025 e fevereiro de 2026 em bases científicas internacionais. Inicialmente foram identificados 216 registros, que passaram por procedimentos sistemáticos de triagem com base em critérios explícitos de inclusão e exclusão, resultando em um corpus analítico final composto por 25 estudos que investigam interações entre estrutura da paisagem, biodiversidade e produtividade agrícola. Os resultados indicam que heterogeneidade espacial, conectividade de habitats e presença de áreas naturais aumentam significativamente a provisão de serviços ecossistêmicos, especialmente polinização e controle biológico de pragas. Esses processos ecológicos contribuem não apenas para maior produtividade, mas também para maior estabilidade da produção agrícola diante de variações ambientais. Conclui-se que a resiliência agrícola depende fortemente da estrutura ecológica das paisagens, destacando a importância do planejamento de paisagens agrícolas biodiversas como estratégia fundamental para fortalecer a estabilidade dos sistemas alimentares em um cenário de mudanças ambientais globais.

Palavras-chave: *Serviços Ecossistêmicos. Biodiversidade Agrícola. Conectividade da Paisagem. Estabilidade Produtiva. Agricultura Sustentável.*

1 INTRODUCTION

During the twentieth century, global agricultural development was largely shaped by the Green Revolution paradigm, which emphasized yield maximization through monocultures supported by synthetic fertilizers, pesticides, and improved crop varieties. While this model substantially increased food production, it also generated structural ecological vulnerabilities, including biodiversity loss, degradation of ecosystem functions, and growing dependence on external inputs. As agricultural systems became progressively simplified, key ecological processes that historically supported crop production were weakened (Tscharntke et al., 2012).

In response, agricultural science has increasingly turned toward ecological

intensification, which seeks to enhance productivity by mobilizing ecological processes rather than replacing them with technological substitutes. Within this framework, biodiversity and ecosystem services are understood as central components of resilient production systems (Bommarco et al., 2013). Agroecology has emerged as a key approach in this transition, promoting diversified farming systems capable of maintaining productivity while strengthening ecological regulation and reducing input dependence (Altieri; Nicholls, 2020). In such systems, biodiversity supports functions such as pollination, nutrient cycling, and biological pest control, contributing to more stable production in complex agricultural landscapes (Perfecto; Vandermeer, 2010).

The resilience of agroecosystems cannot be understood solely at the scale of individual farms. Instead, it depends on the spatial context in which agricultural fields are embedded. Landscape ecology provides a framework for analyzing how habitat distribution, land-use composition, and spatial configuration influence ecological processes operating across agricultural mosaics.

Research increasingly shows that heterogeneous landscapes containing natural or semi-natural habitats can function as reservoirs of functional biodiversity, supporting pollinators and natural enemies that provide essential ecosystem services to crops (Fahrig et al., 2015). In contrast, simplified agricultural landscapes dominated by extensive monocultures tend to limit species movement and reduce the reliability of these services.

Functional connectivity is therefore a critical dimension of landscape structure. Corridors and habitat mosaics facilitate organism movement and maintain ecological flows that sustain pollination and biological pest control. Consequently, the spatial design of agricultural landscapes has become a key determinant of ecosystem service availability and agroecosystem resilience (Landis, 2017). Integrating landscape ecological principles into agricultural management has thus been proposed as a pathway to reconcile biodiversity conservation with agricultural productivity (Jeanneret et al., 2021).

Despite growing recognition of ecosystem services in agriculture, an important conceptual gap persists in the literature. Most studies focus on average crop productivity, assessing whether biodiversity enhances yield levels. However, far fewer studies examine temporal stability of production, a dimension that may be even more critical under increasing climatic variability.

Agricultural systems are increasingly exposed to droughts, heat waves, and other

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climatic disturbances. Under these conditions, the ability of agroecosystems to maintain stable yields may be more relevant for food security than occasional productivity peaks. Ecological theory suggests that biodiversity can stabilize ecosystem functioning through functional redundancy and complementary interactions among species.

Ecosystem services such as pollination and biological pest control are central to this stabilizing role. Wild pollinators significantly enhance fruit set and crop productivity across many agricultural systems (Garibaldi et al., 2013), while landscape structure strongly influences the effectiveness of pollination and pest regulation services (Ricketts et al., 2008). However, the role of landscape configuration in stabilizing these services, and consequently agricultural yields, remains insufficiently synthesized.

Addressing this gap requires examining how landscape structure influences not only the magnitude but also the stability of ecosystem services and agricultural yields. In particular, the proportion of natural habitats and the degree of landscape connectivity may determine the capacity of agroecosystems to buffer environmental disturbances through ecological processes operating across spatial scales.

This study therefore addresses the following research question: To what extent do landscape connectivity metrics and the proportion of natural habitat within agricultural matrices determine the resilience of agroecological yields through the stabilization of ecosystem services?

To answer this question, this article conducts an integrative review of the international literature on landscape ecology, agroecology, and ecosystem service dynamics. The objective is to synthesize global evidence on how landscape configuration influences the stability of key ecosystem services, especially pollination and biological pest control, and how these processes contribute to resilient agricultural production and food security in the context of increasing environmental change.

2 METHODOLOGY

2.1 Integrative review design

This study adopts an integrative literature review approach to synthesize and critically analyze the scientific evidence linking landscape ecology, ecosystem services,

and agroecological yield stability. Integrative reviews are particularly suitable for addressing complex socioecological questions because they allow the inclusion and synthesis of empirical studies with diverse methodological designs while enabling the development of conceptual frameworks and analytical interpretations that extend beyond descriptive literature summaries. In contrast to systematic reviews restricted to narrowly defined experimental designs, integrative reviews facilitate the examination of heterogeneous bodies of knowledge and support the construction of mechanistic interpretations across disciplinary boundaries.

Methodologically, the review followed a structured and transparent process including problem identification, literature search, study screening, data extraction, and analytical synthesis. This procedure is consistent with established frameworks for integrative reviews that emphasize methodological rigor, transparency in study selection, and the development of conceptual synthesis capable of advancing theoretical understanding (Whittemore; Knafl, 2005).

In addition, operational guidelines for conducting integrative reviews in health and social sciences were adopted to ensure systematic organization of the research stages, including explicit inclusion and exclusion criteria and structured data extraction procedures (Souza et al., 2010). Finally, the analytical phase incorporated principles of integrative literature synthesis aimed at identifying conceptual patterns, mechanisms, and explanatory relationships across the selected studies, thereby enabling the development of an interpretative framework rather than a purely descriptive compilation of findings (Torraco, 2005).

Following these methodological principles, the present review seeks to generate a conceptual synthesis of how landscape structure influences ecosystem service dynamics and agroecological yield stability, thereby contributing to the theoretical integration between landscape ecology and agroecosystem resilience research.

2.2 Search strategy and databases

The bibliographic search was conducted between November 2025 and February 2026 in four international scientific databases widely recognized for their coverage of ecological and agricultural research: Web of Science (Clarivate Analytics), Scopus

(Elsevier), ScienceDirect (Elsevier) and CAB Abstracts (CABI).

These databases were selected because they collectively provide extensive coverage of interdisciplinary research on landscape ecology, biodiversity conservation, agroecology, ecosystem services, and agricultural sustainability.

Search queries were conducted in English to ensure broad international coverage of the literature. Boolean operators were used to combine descriptors related to landscape structure, agroecosystems, ecosystem services, and agricultural productivity. The primary search string applied across the databases was structured as follows:

- ("landscape ecology" OR "spatial heterogeneity" OR "landscape connectivity")
- AND ("agroecology" OR "agroecosystem" OR "diversified farming")
- AND ("yield stability" OR "agricultural resilience" OR "food security")
- AND ("ecosystem services" OR "pollination" OR "biological control")

The search strategy was designed to capture studies examining the interaction between landscape configuration and ecosystem service dynamics within agricultural systems. Database filters were not initially applied in order to maximize sensitivity and avoid the premature exclusion of potentially relevant studies.

The initial search retrieved 216 records across the four databases. These records were exported to a reference management system, where duplicate entries were identified and removed prior to the screening stage. Titles and abstracts were subsequently examined to assess their relevance to the research objectives, followed by full-text evaluation of potentially eligible studies.

2.3 Inclusion and analytical criteria

To ensure analytical consistency and alignment with the research question, explicit inclusion and exclusion criteria were applied during the screening process. These criteria were designed to prioritize studies addressing landscape-scale ecological processes that influence ecosystem service provision and agricultural productivity.

Inclusion criteria: a) Empirical studies examining agricultural systems or agroecosystems; b) Studies analyzing landscape-scale variables, such as habitat composition, spatial heterogeneity, or landscape connectivity; c) Research investigating

ecosystem services directly related to agricultural production, particularly pollination and biological pest control; d) Studies presenting measurable outcomes related to agricultural productivity, including yield, fruit set, crop quality, or indicators of yield stability; and e) Peer-reviewed scientific articles, books, or scholarly publications with clearly defined methodologies.

Exclusion criteria: a) Studies focused exclusively on farm-level management without consideration of landscape contexto; b) Conceptual or theoretical papers lacking empirical data related to ecosystem service dynamics; c) Research addressing ecosystem services unrelated to agricultural productivity; d) Studies not examining interactions between biodiversity, landscape structure, and crop production; and e) Duplicated records or publications lacking sufficient methodological transparency.

During the analytical phase, particular attention was given to studies addressing ecosystem service mechanisms relevant to agroecosystem resilience. The review prioritized studies examining the following key variables:

- Effective pollination, measured through indicators such as fruit set, seed production, or crop quality.

- Biological pest control, including predator and parasitoid activity influencing pest suppression.

- Yield stability, referring to temporal consistency of agricultural productivity across environmental variability.

- Functional biodiversity, including diversity of pollinators and natural enemies contributing to ecosystem service provision.

Through this screening process, a final corpus of 25 studies was selected for detailed integrative analysis.

2.4 Data extraction and analytical framework

Data extraction followed a structured analytical framework designed to systematically compare ecological mechanisms across the selected studies. Each article included in the final corpus was examined in detail to extract information related to landscape context, ecosystem service mechanisms, crop systems, and indicators of

agricultural productivity.

To ensure analytical consistency, a standardized data extraction matrix was developed. The matrix organized key attributes of each study, including the spatial context of the landscape, the ecosystem services examined, the crop systems analyzed, and the indicators used to evaluate agricultural productivity or yield stability. This structured approach facilitated cross-study comparison and enabled the identification of recurring ecological mechanisms linking landscape configuration to ecosystem service provision and agroecosystem resilience.

The analytical matrix also allowed the identification of patterns in how landscape composition and connectivity influence ecological interactions, including the movement of pollinators and natural enemies across agricultural mosaics. These patterns were subsequently synthesized to construct a conceptual interpretation of how landscape structure contributes to the stabilization of ecosystem services and agricultural yields.

Table 1 presents the analytical synthesis of the 25 studies included in the integrative review. The table organizes the literature according to key analytical dimensions relevant to the research question, including landscape context, ecosystem services investigated, crop or agroecosystem systems analyzed, and the principal findings reported in each study. This structure allows a systematic comparison of empirical evidence linking landscape configuration, biodiversity-mediated ecosystem services, and agricultural productivity. By synthesizing these attributes across the selected studies, the table provides a transparent overview of the conceptual and empirical foundations supporting the integrative analysis developed in this article.

Table 1 - Analytical Synthesis of Studies on Landscape Ecology and Agroecosystem Services

Study	Landscape Context	Ecosystem Service	Crop / Agroecosystem Context	Main Findings
Altieri & Nicholls (2020)	Diversified agroecological landscapes	Multiple ecosystem services	Agroecological farming systems	Biodiversity-based farming enhances ecological regulation and resilience of food systems.
Altieri, Nicholls & Holt-Giménez (2015)	Climate-sensitive agricultural landscapes	Pest regulation, soil processes	Climate-resilient agroecosystems	Diversified agroecosystems improve adaptive capacity to climatic variability.
Bommarco, Kleijn &	Heterogeneous agricultural	Pollination, pest control	Various crop systems	Ecological intensification increases productivity while

Potts (2013)	landscapes			maintaining ecosystem services.
Estrada-Carmona et al. (2022)	Complex agricultural landscapes	Biodiversity-mediated services	Multiple crop systems	Landscape complexity increases biodiversity and strengthens ecosystem service stability.
Fahrig et al. (2015)	Heterogeneous landscapes with natural habitats	Biodiversity support	Agricultural mosaics	Functional landscape heterogeneity promotes biodiversity conservation and ecosystem functioning.
Garibaldi et al. (2013)	Landscapes with diverse pollinator habitats	Pollination	Global crop systems	Wild pollinators significantly increase crop fruit set independent of honey bee abundance.
Garibaldi et al. (2014)	Agricultural landscapes with natural habitat remnants	Pollination	Multiple crops	Conservation of pollinator habitats enhances agricultural productivity.
Jeanneret et al. (2021)	Agroecological landscapes	Multiple ecosystem services	Agricultural mosaics	Integrating landscape ecology improves ecosystem service management.
Klein et al. (2007)	Pollinator-dependent landscapes	Pollination	Global crops	Many crops depend strongly on animal pollinators for production.
Kremen & Miles (2012)	Diversified vs conventional landscapes	Pollination and pest regulation	Diversified farming systems	Biodiversity-rich farming systems improve ecosystem service delivery.
Landis (2017)	Landscapes designed for biodiversity	Biological pest control	Agricultural landscapes	Landscape planning can enhance natural enemy populations and pest suppression.
Martin et al. (2019)	European agricultural landscapes	Multiple ecosystem services	European crop systems	Landscape composition and configuration jointly regulate biodiversity services.
Perfecto & Vandermeer (2010)	Agroecological matrix landscapes	Multiple ecosystem services	Smallholder agroecosystems	Agroecological landscapes provide alternatives to land-sparing models.
Potts et al. (2010)	Global agricultural landscapes	Pollination	Pollinator-dependent crops	Pollinator decline threatens agricultural productivity and food security.
Ricketts et al. (2008)	Landscapes with varying natural habitat	Pollination	Multiple crops	Proximity to natural habitats increases pollination services in agriculture.
Santos et al. (2021)	Anthropocene agricultural landscapes	Biodiversity-based services	Agroecosystems	Landscape ecology provides tools to reconcile agriculture and biodiversity conservation.
Tscharntke et al. (2012)	Complex agricultural landscapes	Multiple ecosystem services	Global agricultural systems	Biodiversity enhances ecosystem functioning and agricultural sustainability.
Tscharntke et al. (2016)	Landscapes with varying natural habitat cover	Biological pest control	Agricultural systems	Habitat availability influences effectiveness of natural enemies.
Tscharntke	Global	Ecosystem	Food production	Biodiversity conservation

et al. (2012b)	agricultural landscapes	services	systems	and food production are interdependent.
Vandermeer & Perfecto (2017)	Complex agroecological landscapes	Multiple ecosystem services	Agroecological systems	Ecological complexity stabilizes agroecosystem dynamics.
Williams et al. (2010)	Disturbed agricultural landscapes	Pollination	Bee-dependent crops	Bee traits influence species resilience to environmental disturbance.
Zhang et al. (2007)	Agricultural ecosystems	Multiple services and disservices	Crop systems	Ecosystem services strongly influence agricultural productivity and sustainability.
Souza, Silva & Carvalho (2010)	Integrative review methodology	Methodological synthesis	Literature reviews	Integrative reviews allow systematic synthesis of diverse evidence.
Torraco (2005)	Integrative literature review methodology	Conceptual synthesis	Literature reviews	Integrative reviews enable development of theoretical frameworks.
Whittemore & Knafl (2005)	Integrative review framework	Methodological synthesis	Literature reviews	Structured integrative reviews ensure methodological rigor in evidence synthesis.

Source: The authors themselves.

The synthesis reveals consistent evidence that landscape heterogeneity and biodiversity are central drivers of ecosystem service provision in agricultural systems. Across diverse geographical contexts and crop systems, studies highlight the importance of natural habitat patches, landscape connectivity, and diversified farming systems for sustaining pollination and biological pest control services. Research on pollinator dynamics demonstrates that wild pollinators significantly enhance crop productivity and that landscape composition strongly influences their abundance and effectiveness.

Similarly, studies on natural enemies indicate that landscape complexity can strengthen biological pest control by supporting predator and parasitoid communities. Collectively, the reviewed literature suggests that agroecosystem resilience emerges from the interaction between biodiversity, landscape structure, and ecological processes operating across spatial scales, reinforcing the argument that agricultural sustainability depends not only on farm-level management but also on the broader ecological configuration of agricultural landscapes.

3 RESULTS

3.1 Landscape heterogeneity as a reservoir of functional biodiversity

The integrative analysis of the selected studies reveals a consistent pattern: landscape heterogeneity functions as a critical ecological infrastructure that sustains biodiversity and stabilizes ecosystem services in agricultural systems. Across diverse agroecological contexts, landscapes containing a mosaic of croplands, semi-natural habitats, forests, hedgerows, and grasslands provide ecological niches that support functional biodiversity essential to agroecosystem functioning.

A key mechanism identified in the literature is the role of natural habitat patches as reservoirs of beneficial organisms, including pollinators and natural enemies of crop pests. Empirical evidence indicates that heterogeneous landscapes sustain higher biodiversity levels than simplified monocultural landscapes. For example, a large-scale analysis of complex agricultural landscapes demonstrated that biodiversity levels in heterogeneous landscapes can be significantly higher than in simplified systems, reinforcing the importance of spatial complexity for ecological resilience (Estrada-Carmona et al., 2022). As the authors emphasize, "complex agricultural landscapes can harbor high levels of biodiversity while maintaining productive farming systems" (Estrada-Carmona et al., 2022, p. 1).

The ecological significance of landscape heterogeneity has been widely recognized in landscape ecology. Studies show that biodiversity patterns are strongly influenced by landscape composition and configuration, particularly the presence of natural or semi-natural habitat fragments embedded within agricultural matrices. These habitat patches act as refuges and reproduction sites for pollinators and predators, enabling the persistence of ecological interactions essential to crop production (Fahrig et al., 2015). In this sense, biodiversity conservation within agricultural landscapes is not merely a conservation issue but a fundamental component of agroecosystem functionality.

The reviewed literature also highlights the role of heterogeneous landscapes in maintaining diverse communities of natural enemies, including parasitoids, predatory insects, and birds that regulate pest populations. Landscape-level biodiversity contributes

to ecological regulation by increasing the abundance and diversity of organisms capable of suppressing agricultural pests (Tscharntke et al., 2012). This dynamic reflects what has been described as a "landscape moderation" effect, in which biodiversity patterns and ecosystem processes are shaped by spatial configuration at broader scales.

Furthermore, landscape ecology research conducted in the Anthropocene context emphasizes that agricultural sustainability increasingly depends on understanding and managing these spatial ecological interactions. As argued by Santos et al. (2021, p. 4), "landscape ecology provides essential insights for reconciling biodiversity conservation with agricultural production in human-dominated landscapes." This perspective reinforces the idea that the ecological functioning of agroecosystems cannot be understood solely at the scale of individual farms but must be analyzed within the broader spatial structure of agricultural landscapes.

Taken together, the studies reviewed demonstrate that landscape heterogeneity enhances functional biodiversity and strengthens ecosystem service provision, particularly pollination and biological pest control. These findings suggest that maintaining or restoring natural habitat patches within agricultural landscapes is a critical strategy for increasing the ecological resilience of agroecosystems.

3.2 Functional connectivity and ecosystem service flows

Beyond the mere presence of habitat patches, the connectivity between these habitats plays a crucial role in enabling the movement of organisms and the flow of ecosystem services across agricultural landscapes. Functional connectivity determines the extent to which organisms such as pollinators and natural enemies can disperse between habitats and crop fields, thereby influencing the spatial dynamics of ecosystem service provision.

Research in landscape ecology consistently demonstrates that ecological corridors and permeable agricultural matrices facilitate the movement of species across landscapes. This movement is essential for maintaining ecological interactions that support agricultural productivity. For example, studies on biodiversity-based pest control indicate that natural enemies often rely on non-crop habitats for overwintering, reproduction, and refuge from agricultural disturbances (Landis, 2017). Consequently, landscapes lacking

ecological connectivity may experience reduced pest regulation capacity due to limited dispersal of beneficial organisms.

Empirical analyses conducted across European agricultural landscapes reveal that both landscape composition and spatial configuration influence ecosystem service dynamics. In particular, the proportion of natural habitat and the spatial arrangement of habitat patches jointly determine biodiversity patterns and the effectiveness of ecological functions (Martin et al., 2019). The authors demonstrate that ecosystem services emerge from complex interactions between local management practices and landscape-level processes, highlighting the need for multi-scale approaches to agroecosystem management.

Similarly, research on agroecological landscapes emphasizes that integrating landscape ecological principles into agricultural planning can significantly enhance ecosystem service provision. According to Jeanneret et al. (2021, p. 2425), "agroecological landscapes represent an opportunity to integrate biodiversity conservation and ecosystem service management within productive agricultural systems." This perspective underscores the importance of designing agricultural landscapes that promote ecological connectivity and functional biodiversity.

Collectively, the reviewed studies indicate that functional connectivity is a key determinant of ecosystem service flows, enabling pollinators and natural enemies to move across agricultural landscapes and sustain ecological processes critical to crop production.

Table 2 synthesizes the empirical evidence relating landscape structural metrics to ecosystem service responses in agricultural systems. The table organizes the reviewed studies according to five analytical dimensions: landscape metric, ecosystem service affected, observed ecological mechanism, empirical evidence from the literature, and implications for agroecosystem management.

This structure allows the comparison of how specific landscape atributes, such as habitat proportion, spatial heterogeneity, and ecological connectivity, influence the provision of key ecosystem services. By systematically linking landscape configuration with ecological mechanisms and agricultural outcomes, the table provides a concise overview of the spatial determinants of ecosystem service stability in agricultural landscapes.

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Table 2 - Landscape Metrics and Ecosystem Service Responses in Agricultural Landscapes

Landscape Metric	Ecosystem Service Affected	Observed Ecological Mechanism	Empirical Evidence	Implications for Agroecosystems
Proportion of natural habitat	Pollination	Natural habitats provide nesting sites and floral resources that sustain wild pollinator populations	Landscapes with higher natural habitat cover support greater pollinator diversity and higher fruit set (Garibaldi et al., 2013; Klein et al., 2007)	Maintaining ≥20–30% semi-natural habitat improves pollination reliability and crop productivity
Landscape heterogeneity	Biodiversity support and multiple services	Spatial heterogeneity increases habitat diversity and ecological niches for beneficial organisms	Heterogeneous landscapes sustain higher biodiversity levels and stronger ecosystem service provision (Fahrig et al., 2015; Estrada-Carmona et al., 2022)	Diversified landscapes enhance ecological resilience and service stability
Habitat connectivity	Pollination and biological control	Ecological corridors enable dispersal of pollinators and natural enemies across landscapes	Connectivity improves movement of beneficial species and strengthens ecosystem service flows (Landis, 2017; Martin et al., 2019)	Landscape planning should prioritize corridors and permeable agricultural matrices
Landscape complexity	Biological pest control	Natural enemy communities depend on access to non-crop habitats for reproduction and refuge	Increased natural habitat availability enhances predator and parasitoid abundance (Tscharntke et al., 2016)	Pest suppression improves when landscapes maintain ecological complexity
Agricultural matrix diversity	Multiple ecosystem services	Diversified agroecosystems support complementary ecological interactions among species	Biodiversity-rich agricultural matrices enhance ecosystem service delivery (Kremen; Miles, 2012; Perfecto; Vandermeer, 2010)	Agroecological diversification strengthens ecosystem functioning and yield stability

Source: The authors themselves.

The synthesis presented in Table 2 reveals a consistent pattern across the reviewed literature: landscape structure strongly mediates the availability and reliability of ecosystem services essential for agricultural productivity. Studies repeatedly show that landscapes containing higher proportions of natural habitats support more diverse communities of pollinators and natural enemies, thereby strengthening pollination and biological pest control services (Garibaldi et al., 2013; Klein et al., 2007; Tscharntke et al., 2016).

Similarly, landscape heterogeneity and ecological connectivity facilitate the movement of organisms across agricultural mosaics, enabling ecosystem service flows

that stabilize agroecosystem functioning (Fahrig et al., 2015; Landis, 2017; Martin et al., 2019). Importantly, the evidence also indicates that ecosystem services are not determined solely by local farm management but by the broader spatial configuration of agricultural landscapes. This reinforces the growing recognition that sustainable agriculture depends on landscape-scale ecological processes, suggesting that agroecosystem resilience emerges from the interaction between biodiversity, habitat connectivity, and diversified agricultural matrices (Kremen; Miles, 2012; Perfecto; Vandermeer, 2010).

3.3 Pollination stability in agricultural landscapes

Pollination represents one of the most extensively studied ecosystem services in agricultural landscapes. The reviewed literature provides strong empirical evidence that wild pollinators play a critical role in sustaining crop productivity and stability, particularly in landscapes that maintain natural habitats.

One of the most influential global studies on pollination services demonstrated that wild pollinators significantly increase fruit set in agricultural crops regardless of the presence of managed honey bees. In a large international dataset spanning multiple crop systems, wild pollinators enhanced crop productivity across diverse agricultural landscapes (Garibaldi et al., 2013). As the authors state, "wild pollinators enhance fruit set of crops regardless of honey bee abundance" (Garibaldi et al., 2013, p. 1608). This finding challenges the assumption that managed pollinators alone can sustain pollination services in intensive agricultural systems.

Subsequent research further emphasized the importance of conserving pollinator habitats within agricultural landscapes. Studies indicate that the availability of natural habitats surrounding agricultural fields significantly influences pollinator diversity and pollination efficiency (Garibaldi et al., 2014). Landscapes containing forests, grasslands, or semi-natural habitats tend to support more diverse and abundant pollinator communities, thereby strengthening pollination services.

Earlier global assessments also demonstrated that a large proportion of the world's major crops depend, at least partially, on animal pollinators. According to Klein et al. (2007), approximately 75% of leading global crops benefit from animal-mediated

pollination, highlighting the central importance of pollinator biodiversity for global food production.

However, pollinator populations are increasingly threatened by habitat loss, pesticide use, and climate change. Species-specific traits influence the resilience of pollinator populations to environmental disturbances, meaning that some pollinator species may be more vulnerable to landscape simplification than others (Williams et al., 2010). Consequently, landscapes that maintain diverse pollinator communities are more likely to sustain stable pollination services across environmental fluctuations.

These findings collectively suggest that landscape-level biodiversity is a key determinant of pollination stability, reinforcing the argument that agricultural productivity depends not only on local management but also on broader ecological conditions.

3.4 Biological control and pest regulation

Biological pest control represents another crucial ecosystem service linking biodiversity conservation to agricultural productivity. The integrative review indicates that the abundance and diversity of natural enemies, such as predators, parasitoids, and insectivorous birds, are strongly influenced by landscape structure and habitat availability.

Research shows that landscapes containing natural habitats support more diverse communities of natural enemies capable of regulating pest populations in agricultural fields. These organisms often depend on non-crop habitats for refuge, reproduction, or alternative food sources. As a result, the presence of natural habitats in agricultural landscapes can significantly enhance pest suppression (Landis, 2017).

However, the relationship between landscape structure and pest control is not always linear. In some cases, increased natural habitat availability does not necessarily translate into stronger pest regulation if ecological interactions between predators, pests, and crops are disrupted. Empirical analyses demonstrate that the effectiveness of biological control depends on complex ecological dynamics influenced by landscape composition, habitat configuration, and species interactions (Tscharntke et al., 2016).

Ecosystem services in agricultural systems often involve trade-offs and

interactions between beneficial and detrimental processes. Agricultural landscapes simultaneously generate ecosystem services, such as pollination and pest control, and ecosystem disservices, including pest outbreaks or competition for resources (Zhang et al., 2007). Understanding these interactions is therefore essential for designing agricultural landscapes capable of maximizing beneficial services while minimizing ecological risks.

Overall, the reviewed evidence indicates that biological pest control is strongly mediated by landscape-level ecological processes, reinforcing the need for agricultural systems that maintain functional biodiversity and ecological connectivity. These findings further support the broader argument that agroecosystem resilience emerges from the interaction between landscape structure, biodiversity, and ecosystem service dynamics operating across spatial scales.

4 DISCUSSION

4.1 The insurance hypothesis in agroecosystems

The results synthesized in this review provide strong empirical support for the insurance hypothesis, which posits that biodiversity stabilizes ecosystem functioning by providing functional redundancy and complementary ecological interactions. In agroecosystems, this hypothesis implies that biodiversity does not merely increase average productivity but enhances the temporal stability of ecosystem services, thereby reducing the risk of production collapse under environmental variability.

Evidence from ecological intensification studies suggests that diversified agricultural landscapes sustain more stable ecosystem service provision than simplified monocultures. As highlighted by Bommarco; Kleijn; Potts (2013, p. 231), ecological intensification seeks to "harness ecosystem services for food security," recognizing biodiversity as a functional component of productive agricultural systems. Their synthesis indicates that pollination, biological pest control, and nutrient cycling can collectively contribute to stable agricultural productivity when biodiversity is maintained within agricultural landscapes.

Similarly, comparative analyses of diversified and conventional farming systems

show that biodiversity-rich agricultural systems tend to deliver multiple ecosystem services simultaneously. According to Kremen; Miles (2012, p. 40), diversified farming systems "can provide high levels of ecosystem services while maintaining agricultural production." Such systems reduce dependency on external inputs and enhance ecological regulation, thereby strengthening the resilience of agroecosystems to environmental disturbances.

The theoretical foundations of this stabilizing effect are further elaborated in agroecological research emphasizing ecological complexity as a key property of resilient agroecosystems. Vandermeer; Perfecto (2017, p. 42) argue that agroecosystems should be understood as complex ecological systems in which "biodiversity and ecological interactions generate stability and resilience in production systems." Within this framework, biodiversity acts as a form of ecological insurance, buffering agroecosystems against disturbances by ensuring that multiple species can perform similar ecological functions under varying environmental conditions.

Taken together, these findings suggest that agricultural resilience emerges from the interaction between biodiversity, landscape structure, and ecological processes operating across spatial scales. This perspective challenges conventional agricultural paradigms centered solely on productivity maximization and highlights the importance of designing agricultural landscapes capable of sustaining ecological processes that stabilize food production over time.

4.2 Ecosystem service synergies

Another important insight emerging from the reviewed literature concerns the synergistic interactions between ecosystem services operating within agricultural landscapes. Pollination and biological pest control are often treated as separate ecological processes; however, empirical evidence indicates that these services frequently interact and reinforce one another within complex agroecosystems.

Research on pollination services demonstrates that the conservation of natural habitats within agricultural landscapes significantly enhances pollinator diversity and crop productivity. For example, studies on pollinator-mediated crop production show that maintaining habitats for wild pollinators can increase both fruit set and yield stability in

multiple crop systems (Garibaldi et al., 2014). As the authors emphasize, "managing agricultural landscapes to support wild pollinators can improve both crop yield and yield stability" (Garibaldi et al., 2014, p. 442).

At the same time, landscape structure influences the abundance and effectiveness of natural enemies responsible for biological pest control. These organisms often rely on semi-natural habitats as refuge areas and dispersal corridors, allowing them to move into agricultural fields where they suppress pest populations. Importantly, these ecological interactions rarely operate in isolation. Pollinator habitats, for example, frequently support predator and parasitoid communities that contribute to pest regulation.

Large-scale analyses of European agricultural landscapes show that the interaction between landscape composition and configuration determines the combined performance of multiple ecosystem services (Martin et al., 2019). The authors demonstrate that biodiversity-mediated services are shaped by multi-scale ecological processes, emphasizing that "landscape composition and configuration jointly regulate biodiversity and ecosystem services across agricultural landscapes" (Martin et al., 2019, p. 1084).

These findings reinforce the importance of considering ecosystem services as interconnected ecological networks rather than isolated processes. The stability of agricultural production therefore depends not only on individual ecosystem services but also on the synergistic interactions among them.

4.3 Agroecological landscapes and climate resilience

The interaction between landscape ecology and agroecology also has profound implications for climate resilience in agricultural systems. As climate change intensifies the frequency of extreme events, such as droughts, heat waves, and irregular precipitation, agroecosystems increasingly require mechanisms capable of buffering environmental variability.

Agroecological research emphasizes that diversified farming systems embedded in heterogeneous landscapes are better able to adapt to climatic stress. According to Altieri; Nicholls; Holt-Giménez (2015, p. 870), agroecological systems "enhance the resilience of farming systems to climatic variability through biodiversity and ecological interactions." Such systems rely on ecological processes, rather than external inputs, to

regulate pests, maintain soil fertility, and sustain crop productivity under changing environmental conditions.

Recent analyses also highlight the importance of agroecology in reconstructing resilient food systems in the face of global environmental crises. Altieri; Nicholls (2020, p. 882) argue that agroecology represents a pathway toward rebuilding agricultural systems capable of addressing both ecological degradation and social vulnerabilities associated with industrial agriculture. In this sense, agroecology functions not only as a set of farming practices but as a broader framework for designing resilient socioecological food systems.

The importance of landscape complexity for climate resilience is also supported by empirical evidence demonstrating that complex agricultural landscapes sustain higher biodiversity and ecosystem service provision than simplified agricultural systems. Estrada-Carmona et al. (2022, p. 3) note that "complex agricultural landscapes can simultaneously support biodiversity conservation and productive agriculture," highlighting the potential of landscape-level strategies to enhance ecological resilience.

Table 3 synthesizes the conceptual relationships between landscape ecological attributes, ecosystem service dynamics, agricultural yield stability, and food security outcomes identified in the reviewed literature. The table organizes empirical findings according to key landscape attributes—including habitat proportion, landscape heterogeneity, connectivity, and agroecological diversification—and links these spatial characteristics to ecosystem service provision and their implications for agricultural production. By integrating ecological mechanisms with agricultural outcomes, the table highlights how landscape structure shapes the stability of ecosystem services that underpin food production systems.

Table 3 - Landscape Ecology Mechanisms and Food Security Outcomes

Landscape Attribute	Ecosystem Service	Yield Stability Effect	Food Security Implication	Supporting Evidence
High proportion of semi-natural habitats	Pollination	Greater fruit set, seed production, and reduced variability in crop yields	Improved stability of production in pollinator-dependent crops	Garibaldi et al. (2013); Klein et al. (2007)
Landscape heterogeneity (diverse land-use mosaic)	Multiple ecosystem services (pollination, pest regulation)	Increased functional redundancy and ecological buffering against disturbances	Greater resilience of agroecosystems to environmental variability	Fahrig et al. (2015); Estrada-Carmona et al. (2022)

Habitat connectivity and ecological corridors	Pollination and biological control	Enhanced dispersal of pollinators and natural enemies across landscapes	Stabilized ecosystem service flows supporting consistent yields	Landis (2017); Martin et al. (2019)
Diversified agroecological matrices	Multiple ecosystem services	Synergistic ecological interactions improving regulation of pests and pollination	Reduced dependence on external inputs and increased production resilience	Kremen; Miles (2012); Perfecto; Vandermeer (2010)
Biodiversity-rich agricultural landscapes	Pest regulation and pollination	Enhanced ecological regulation of pest populations and improved crop productivity	Strengthened food system resilience under climatic and ecological stress	Bommarco; Kleijn; Potts (2013); Altieri; Nicholls (2020)

Source: The authors themselves.

The synthesis presented in Table 3 reinforces the central argument of this study: landscape configuration plays a decisive role in determining the stability and resilience of agricultural production systems. The reviewed evidence consistently demonstrates that landscapes containing higher proportions of natural habitats and greater spatial heterogeneity support richer biodiversity and more stable ecosystem service provision (Fahrig et al., 2015; Estrada-Carmona et al., 2022).

These ecological conditions enhance the abundance and effectiveness of pollinators and natural enemies, which in turn contribute to more stable crop yields (Garibaldi et al., 2013; Landis, 2017). Furthermore, diversified agroecological matrices strengthen ecological interactions among species, generating synergistic ecosystem service dynamics that reduce dependence on synthetic inputs and enhance system resilience (Kremen; Miles, 2012; Perfecto; Vandermeer, 2010).

From a food security perspective, these findings suggest that maintaining biodiversity and ecological connectivity within agricultural landscapes is not only an environmental priority but also a fundamental strategy for stabilizing food production under conditions of climatic and ecological uncertainty (Bommarco; Kleijn; Potts, 2013; Altieri; Nicholls, 2020).

4.4 Thresholds of landscape fragmentation

Despite the positive effects of biodiversity and landscape heterogeneity on ecosystem service provision, the reviewed literature also highlights the existence of

ecological thresholds beyond which ecosystem services may collapse. Agricultural landscapes characterized by extreme habitat loss and fragmentation may reach tipping points where ecological processes are no longer able to sustain biodiversity or ecosystem service provision.

Landscape ecology research demonstrates that biodiversity patterns and ecosystem processes are strongly moderated by landscape composition and spatial structure. According to Tscharntke et al. (2012), landscape simplification can significantly reduce biodiversity and disrupt ecological interactions essential for ecosystem functioning. In particular, the loss of semi-natural habitats can limit the availability of nesting sites and resources for pollinators and natural enemies, weakening ecosystem service provision.

Pollinator decline represents a particularly critical example of this phenomenon. Global assessments indicate that pollinator populations are experiencing widespread declines driven by habitat loss, pesticide exposure, and climate change. As emphasized by Potts et al. (2010, p. 345), "pollinator declines have the potential to threaten crop production and ecosystem stability worldwide." Given that approximately three-quarters of the world's leading crops depend to some extent on animal pollination, the erosion of pollinator diversity may have significant implications for global food security.

These findings underscore the importance of maintaining minimum thresholds of natural habitat within agricultural landscapes. Once these thresholds are crossed, ecological restoration becomes increasingly difficult, and the capacity of landscapes to support ecosystem services may be severely compromised.

4.5 Implications for agroecological policy and landscape planning

The evidence synthesized in this review has important implications for agricultural policy and landscape planning. Traditional agricultural policies often focus on farm-level productivity and input efficiency while neglecting the spatial ecological processes that sustain ecosystem services. However, the results of this integrative review suggest that sustainable agriculture requires landscape-scale planning capable of integrating biodiversity conservation with agricultural production.

Agroecological landscape approaches propose the design of agricultural mosaics

in which crop fields coexist with natural and semi-natural habitats that support biodiversity and ecosystem services. According to Perfecto; Vandermeer (2010), such agroecological matrices represent an alternative to the dominant land-sparing paradigm, which seeks to separate conservation and agricultural production into distinct spatial zones. Instead, agroecological landscapes integrate conservation and production within multifunctional landscapes capable of sustaining biodiversity and agricultural productivity simultaneously.

Recent research also emphasizes the importance of incorporating landscape ecological principles into agricultural management and territorial planning. As highlighted by Jeanneret et al. (2021), agroecological landscapes offer a promising framework for integrating biodiversity conservation, ecosystem service provision, and sustainable agricultural production.

Ultimately, these findings suggest that the future of sustainable agriculture will depend not only on technological innovations or improved farm management practices but also on the ecological design of agricultural landscapes. By maintaining biodiversity, enhancing habitat connectivity, and promoting diversified agroecosystems, landscape-scale strategies can strengthen ecosystem service provision and contribute to more resilient and sustainable food systems.

In synthesis, the evidence reviewed throughout this section indicates that the resilience of agricultural production cannot be understood solely through farm-level management practices, but must be analyzed within the broader spatial configuration of agricultural landscapes. Landscape heterogeneity, habitat connectivity, and biodiversity-rich agroecological matrices emerge as critical determinants of ecosystem service stability, particularly for pollination and biological pest control.

These ecological processes function as stabilizing mechanisms that buffer agroecosystems against environmental variability and climatic disturbances. Consequently, the transition toward sustainable food systems requires a shift from input-dependent agricultural intensification to landscape-based agroecological design, in which biodiversity conservation and food production are integrated within multifunctional agricultural landscapes. Recognizing landscapes as ecological infrastructures of food security therefore represents a crucial step toward reconciling agricultural productivity, biodiversity conservation, and long-term resilience of global food systems.

5 CONCLUSION

This integrative review demonstrates that the stability of agricultural production is strongly influenced by the spatial configuration of agricultural landscapes. Across the studies analyzed, consistent evidence indicates that landscape heterogeneity increases the stability of ecosystem services, particularly pollination and biological pest control. Natural habitat patches embedded within agricultural matrices function as ecological reservoirs that sustain functional biodiversity, enabling the persistence of ecological processes essential to crop production.

In addition, landscape connectivity enhances the movement of pollinators and natural enemies, facilitating ecosystem service flows across agricultural mosaics. Together, these mechanisms suggest that complex landscapes reduce the probability of ecological service collapse and, consequently, mitigate fluctuations in agricultural productivity.

The findings synthesized in this study reinforce a central conclusion: the resilience of agricultural systems depends more on landscape structure than on the intensification of external inputs. While conventional agricultural models emphasize technological intensification to maximize productivity, the evidence reviewed here indicates that biodiversity, spatial heterogeneity, and ecological connectivity play a decisive role in stabilizing agroecosystem functioning. From this perspective, landscape ecology emerges as a critical analytical and practical framework for designing agroecosystems capable of maintaining productivity under conditions of environmental variability and climatic uncertainty.

Ultimately, the stability of ecosystem services and agricultural production has direct implications for global food security. Food systems that depend on simplified agricultural landscapes and high external inputs may achieve short-term productivity gains but remain highly vulnerable to ecological disruptions.

In contrast, landscape-based agroecological systems offer a pathway toward more resilient and sustainable food production, as they integrate biodiversity conservation, ecosystem service provision, and agricultural productivity within multifunctional landscapes. Strengthening the ecological infrastructure of agricultural landscapes therefore represents a crucial strategy for ensuring stable food production in an

increasingly uncertain environmental future.

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Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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