Effects of Agricultural Landscape Heterogeneity on Biodiversity and Its Ecosystem Services (Postprint)

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Abstract

Biodiversity holds special significance in agricultural landscapes. This paper first reviews the composition and characteristics of agricultural landscape heterogeneity. Agricultural landscape heterogeneity includes not only spatial compositional and configurational heterogeneity and temporal heterogeneity, but more importantly should include functional heterogeneity of agricultural landscapes based on species or functional group perspectives, which is crucial for discussing the relationship between landscape heterogeneity and biodiversity. A review of the multi-scale effects of landscape spatial and temporal heterogeneity on biodiversity reveals that numerous studies have confirmed that non-agricultural habitats are essential for maintaining biodiversity in agricultural landscapes, and that agricultural landscapes with higher heterogeneity composed of non-agricultural habitat patches and farmland matrix often promote biodiversity, with different taxonomic groups responding to landscape heterogeneity at different scales. The combined influence of landscape structure and interspecific interactions constitutes the mechanism by which heterogeneous agricultural landscapes maintain biodiversity. Landscape heterogeneity influences ecosystem services such as biological control, pollination, and nutrient cycling provided by biodiversity through its effects on the composition and distribution of biodiversity. Based on research findings from a series of studies on the characteristics of agricultural landscape heterogeneity and its impacts on biodiversity in the middle and lower reaches of the Yellow River Plain, future research in agricultural landscapes managed as small plots under the household contract responsibility system should deeply investigate the mechanisms through which agricultural landscapes influence biodiversity and its ecosystem services based on spatiotemporal heterogeneity of functional landscapes, providing scientific foundations for the construction of sustainable agricultural landscapes.

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Preamble

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Effects of Agricultural Landscape Heterogeneity on Biodiversity and Ecosystem Services

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Abstract

Biodiversity in agricultural landscapes holds special significance. This paper first reviews the composition and characteristics of agricultural landscape heterogeneity, which encompasses not only spatial compositional and configurational heterogeneity and temporal heterogeneity, but also functional heterogeneity based on species or functional groups. This functional perspective is crucial for discussing relationships between landscape heterogeneity and biodiversity. Examining the multi-scale effects of spatial and temporal heterogeneity on biodiversity reveals that numerous studies confirm the necessity of non-agricultural habitats for maintaining biodiversity in agricultural landscapes. Landscapes with higher heterogeneity, composed of non-agricultural habitat patches and farmland matrix, generally promote biodiversity, though different taxa respond to landscape heterogeneity at different scales. The combined influence of landscape structure and species interactions forms the mechanism by which heterogeneous agricultural landscapes maintain biodiversity. Landscape heterogeneity subsequently affects ecosystem services such as biological control, pollination, and nutrient cycling through its influence on biodiversity composition and distribution. Building upon a series of studies on agricultural landscape heterogeneity and its effects on biodiversity in the middle and lower reaches of the Yellow River Plain, future research should investigate the mechanisms through which agricultural landscapes affect biodiversity and ecosystem services based on spatio-temporal heterogeneity of functional landscapes, particularly in small-field management systems under the household contract responsibility system. Such research will provide scientific foundations for constructing sustainable agricultural landscapes.

Keywords: Agricultural landscape; Landscape heterogeneity; Biodiversity; Ecosystem services; Middle and lower reaches of the Yellow River

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1. Agricultural Landscape Heterogeneity

Landscape heterogeneity refers to the non-uniform and non-random spatial distribution of landscape structures. Agricultural landscapes are mosaic systems composed of intensive agricultural land and non-agricultural habitats. This multi-scale heterogeneous landscape, formed by different types of non-agricultural habitats and farmland under various management practices, holds significant importance for biodiversity conservation in agricultural ecosystems. Agricultural landscape heterogeneity includes spatial heterogeneity, temporal heterogeneity, and functional heterogeneity. While numerous studies have examined spatial heterogeneity at various scales, research on temporal and functional heterogeneity remains relatively limited.

1.1 Spatial Heterogeneity of Agricultural Landscapes

Spatial heterogeneity comprises two essential components: compositional heterogeneity and configurational heterogeneity. Compositional heterogeneity refers to differences in land use and land cover types, which are more readily observed and understood. In the alluvial plains of the middle and lower Yellow River, for example, agricultural landscapes primarily consist of small fields under conventional management within the household contract responsibility system, along with non-agricultural habitats such as field margins, patchy woodlands, roadside hedgerows, and natural ditches. This landscape heterogeneity epitomizes the farmland shelterbelt network system of the North China Plain, making regional studies highly representative for agricultural landscape-dominated areas. Compositional heterogeneity exhibits strong scale dependence; at the field management level, even smaller-scale heterogeneity emerges from variations in agronomic practices and cropping patterns among small plots under the household contract system.

Configurational heterogeneity represents differences in how various landscape types are arranged—the heterogeneity of landscape structure. For instance, two agricultural regions with identical proportions of non-agricultural habitat may exhibit different configurational heterogeneities due to variations in patch size, shape, and number of farmland and non-agricultural habitats. Such differences affect factors like field boundary length, thereby influencing biodiversity.

1.2 Temporal Heterogeneity of Agricultural Landscapes

Agricultural landscape structure changes over time. Under the influences of global change, urbanization, increasing demand for arable land from growing populations, and intensive farmland use, agricultural landscapes have experienced fragmentation and simplification. In the middle and lower Yellow River region, these changes stem primarily from two pressures. First, food demands from population growth have forced agricultural expansion, converting limited non-agricultural land into cultivated fields—manifested in the disappearance of patchy woodlands and protective shelterbelt hedgerows, and exacerbated by global change impacts such as the loss of natural ditches and ponds. Second, rapid urbanization has created demand for construction land, transforming woodlands and other non-agricultural habitats as well as farmland into built-up areas. Meanwhile, rural-to-urban migration has led to labor shortages and aging populations in "hollow villages," promoting large-scale agriculture with monoculture cropping and intensive inputs of chemical fertilizers, pesticides, and mechanical tillage. This has severely reduced non-agricultural habitats like field boundaries and roadside hedgerows, accentuating landscape simplification. Such structural changes inevitably affect and even endanger biodiversity and ecological functions within agricultural ecosystems. Both the historical context of landscape types and management practices and their post-conversion dynamics influence biodiversity. For example, when non-agricultural habitats are converted to farmland patches, rich weed diversity may persist due to historical seed banks.

1.3 Functional Heterogeneity of Agricultural Landscapes

The same landscape type or habitat provides different resources for different species. While rich natural habitats can offer multiple resources such as food and shelter, farmland habitats typically provide more single-purpose resources like food alone. Different landscape components may serve identical functions for certain species. For example, sparsely vegetated areas with bare ground serve as potential nesting habitats for many ground-nesting birds, and intercropped fields can provide similar conditions—thus both can be treated as the same functional landscape type (nesting habitat). Similarly, open water bodies and construction land are equally unsuitable areas for these birds and can be considered as a single unsuitable functional landscape type. Therefore, agricultural landscapes also exhibit functional landscape heterogeneity. When studying the effects of landscape heterogeneity on biodiversity, it is essential to carefully consider functional heterogeneity based on species-specific differences.

Current research has emphasized compositional heterogeneity, often using the proportional area of certain landscape types as a key factor affecting biodiversity, while paying less attention to configurational heterogeneity. Moreover, case studies examining functional heterogeneity from the perspective of different species remain rare and should represent a future research direction.

2. Effects of Agricultural Landscape Heterogeneity on Biodiversity

Arthropods serve as important environmental indicator taxa in agricultural ecosystems, performing critical ecological functions such as biological control, nutrient cycling, and pollination. For instance, the spatio-temporal distribution patterns of butterflies (Rhopalocera) can reflect different landscape patterns, while ground beetles (Carabidae) are highly sensitive to environmental factors like temperature and humidity, making them valuable bioindicators. Most landscape-biodiversity research has focused on these taxonomic groups.

2.1 Multi-Scale Responses of Biodiversity to Landscape Heterogeneity

Scale represents a core research topic in landscape ecology, and the effects of landscape heterogeneity on biodiversity also exhibit scale-dependent patterns. Forest fragmentation in Mediterranean regions increased local microbial diversity while negatively affecting microbial diversity at the landscape scale. Studies on biodiversity responses to landscape heterogeneity have expanded from habitat and landscape scales to regional and even transboundary scales. Numerous cases have documented that soil fauna, large surface-dwelling arthropods, pollinators, amphibians, mammals, and birds respond to landscape heterogeneity at different characteristic scales.

At the landscape scale (1,500–2,200 m), landscape heterogeneity positively correlates with natural enemy abundance. In the lower Yellow River Plain agricultural landscape, Hymenoptera are the dominant indicator group in woodlands and hedgerows, Araneae in ditches, and Coleoptera in farmland. As scale increases, positive correlations strengthen among dominant surface-dwelling arthropod groups in farmland. Surface arthropods in woodlands and farmland respond to landscape characteristics at 250 m, while hedgerows and ditches respond at 400 m. This likely reflects both the nature of landscape patches and corridors—where corridors (hedgerows and ditches) have landscape connectivity significance and show significant responses to heterogeneity at larger scales, while farmland and woodlands serve as matrix and patches and respond at smaller scales—and differences in species composition and life habits among arthropods in different habitats. Sites with higher landscape heterogeneity host greater numbers of surface-dwelling Coleoptera, with configurational heterogeneity significantly affecting Coleoptera diversity. The interaction between landscape composition and configuration significantly impacts arthropod community abundance ($P<0.05$).

At the local scale, natural enemy abundance is higher in heterogeneous than in homogeneous landscapes. Fields surrounded by complex habitats support higher natural enemy abundance than simplified fields, with abundance increasing closer to field boundaries. Non-agricultural habitat characteristics directly affect natural enemy communities. Because woodland habitats (including orchards) experience less disturbance from agricultural activities like harvesting and tillage compared to non-wooded habitats and annual crop habitats, the presence of woodlands in oversimplified agricultural landscapes can mitigate negative impacts of agricultural intensification on biodiversity by providing refugia.

At the field scale, perennial crop habitats maintain higher biodiversity than annual crop habitats due to weaker disturbance and the provision of overwintering refugia. Spider diversity is higher in organic agriculture with less disturbance compared to conventional agriculture. Thus, different cultivation practices also create landscape heterogeneity that affects spiders and other biodiversity.

2.2 Responses of Biodiversity to Landscape Change

Historical landscape changes, such as land use alterations, inevitably affect biodiversity in agricultural landscapes. Research in the middle and lower Yellow River Plain agricultural landscape found that woodland surface arthropods are sensitive to landscape dynamics at larger scales (250 m, 350 m, and 500 m), including Euclidean distance to habitat (woodland), connectivity, and changes in Simpson' s index.

Short-term landscape changes affect insect density through two mechanisms. Immediately after patch removal, insect population density in remaining patches increases due to crowding effects. Conversely, when patch area increases, insect population density decreases due to dilution effects.

Seasonal landscape dynamics also influence the composition and distribution of non-agricultural biodiversity. Winter vegetation (such as crop cover) can sustain natural enemy communities and enhance their pest control functions. Staggered harvesting or protection of natural enemy overwintering habitats in field management can facilitate non-agricultural organism migration from farmland to non-agricultural habitats during restricted seasons, thereby promoting non-agricultural biodiversity in agricultural landscapes after warming.

Numerous studies confirm that agricultural landscape ecosystems emphasizing only yield, with highly intensive land use, cause negative environmental impacts (such as agricultural pollution) and unsustainable management practices (straw burning, excessive fertilizer and pesticide application) that destroy ecosystem processes and functions, representing important causes of biodiversity loss in agricultural ecosystems. Complex landscapes with rich plant diversity and low human disturbance in non-agricultural habitats maintain more species by providing habitats, resources, shelters, and migration corridors, playing crucial roles in biodiversity conservation. Natural habitats and nectar plants in agricultural landscapes serve as media linking landscapes with pollinators. Pollinators, with their rapid movement and wide ranges, are highly sensitive to the spatiotemporal distribution of different mosaic patches (semi-natural habitats and farmland). Therefore, planning and adjusting farmland and non-agricultural patches, and even constructing and restoring non-agricultural habitats, represent effective approaches for conserving biodiversity in agricultural ecosystems.

3. Mechanisms by Which Agricultural Landscape Heterogeneity Maintains Biodiversity

The combined effects of biological dispersal modes (e.g., wind vs. animal-mediated seed dispersal in plants; crawling, jumping, and flying in animals) and landscape structure (connectivity of semi-natural habitats, density of hedgerows or woodlands, or landscape openness) determine how far species can move through landscapes to reach suitable patches.

3.1 Connectivity and Isolation Mechanisms Based on Landscape Structure

In agricultural landscapes, non-agricultural habitats with continuous tree, shrub, and herbaceous vegetation and litter cover influence abiotic factors such as nutrients, water, and light, creating distinct microclimatic environments that provide organisms with habitats, food sources, overwintering sites, and species sources. As different non-agricultural habitat types enter landscape buffer zones, increased abundance of associated species enhances biodiversity. Because some species can only survive in specific habitats, landscapes with multiple habitat types accommodate more species. Therefore, maintaining high heterogeneity in agricultural landscapes is critically important for biodiversity conservation. This biodiversity increase due to landscape heterogeneity is not necessarily linear. For example, different life stages of an organism may require or prefer different habitats (landscape complementation), or certain habitats may provide supplementary nesting sites and food sources at specific times (landscape supplementation). Amphibians, for instance, require both aquatic and terrestrial environments during tadpole and adult frog stages, thus existing in greater numbers only in landscapes containing both habitat types. Additionally, increased configurational heterogeneity in non-agricultural habitats enhances landscape supplementation effects. Complex patch shapes increase landscape mosaic adjacency and connectivity between potential and supplementary resource sites. Linear woody landscapes such as hedgerows provide habitats for non-agricultural organisms and enhance landscape connectivity, thereby mitigating negative impacts of intensive agriculture.

The loss of non-agricultural habitats in intensive agriculture reduces suitable habitat area and increases isolation. High-intensity land use may block species from surrounding areas, preventing detection of associations between landscape characteristics and field weed vegetation. In the middle and lower Yellow River Plain, woodlands did not show higher abundance or richness of meso- and micro-soil fauna, possibly due to disturbance levels in plantation forests and abundant food resources for soil fauna in farmland. However, species richness and diversity of Formicidae, Coleoptera, and Araneae in woodlands were generally higher than in farmland, with woodlands serving as important winter refugia for arthropods.

3.2 Mechanisms Based on Biological Dispersal and Species Interactions

From different seed dispersal modes in plants to various animal movement patterns—from crawling and jumping in surface-dwelling arthropods to flying in pollinators and migration in birds—differences in dispersal ability and mobility among organisms lead to different characteristic response scales to landscape heterogeneity. Generally, more mobile communities exhibit higher diversity in heterogeneous landscapes at larger scales, while less mobile species are more significantly affected by small-scale habitat differences or even field management heterogeneity.

Landscape heterogeneity also increases biodiversity by influencing species interactions. As dispersal rates among similar habitat patches decrease (i.e., reduced patch crossing probability), the probability of competitor coexistence increases. Increased landscape compositional heterogeneity reduces biological dispersal among similar habitat patches, and lower dispersal rates imply the existence of more metacommunities. Biodiversity consequently increases due to reduced competition.

4. Effects of Agricultural Landscape Heterogeneity on Ecosystem Services

Growing evidence demonstrates that landscape composition is an important driver of insect populations, thereby affecting ecosystem services such as biological control. Landscape complexity and agricultural management influence plant, animal, and microbial diversity, consequently impacting ecosystem services including nutrient cycling, water regulation, and pest suppression provided by beneficial insects.

4.1 Biological Control

Increased landscape heterogeneity is often accompanied by higher abundance or diversity of natural enemies, implying enhanced pest control capacity. Many studies in agricultural ecosystems have found positive correlations between landscape heterogeneity and parasitism/predation rates.

However, natural enemy abundance and richness cannot serve as direct indicators of pest control services. For example, high natural enemy diversity may result in low pest control rates due to intraguild predation, or high control rates may emerge from facilitative effects of other species in the ecosystem. Furthermore, control provided only by specialists may relate more to their abundance than to natural enemy diversity. Regardless of the relationship between biodiversity and ecosystem services, factors affecting natural enemy distribution will influence the ecosystem services they provide to crops. Therefore, discussing landscape diversity effects on biodiversity at the species level can yield valuable conclusions for landscape management research in agricultural ecosystems. Heterogeneous landscapes also affect biological control by influencing temporal dynamics of natural enemy and pest populations. Compared to simple landscapes, natural enemies in complex landscapes appear before aphid population peaks, thereby effectively controlling pest outbreaks. Biological control also includes weed control. Non-agricultural herbivores suppress weeds through seed predation, representing an important ecosystem service of non-agricultural biodiversity. Seed predation is higher in organically managed wheat fields than in conventionally managed fields, suggesting that European agri-environmental schemes designed to protect flowering plant diversity also provide beneficial weed control mechanisms.

4.2 Pollination Services

Landscape simplification severely threatens pollination services provided by flying pollinators. Farmland expansion and the fragmentation and loss of non-agricultural habitats in agricultural landscapes deprive pollinators of essential resources. Large-bodied, functionally effective pollinators are particularly vulnerable to habitat loss, accelerating the decline of pollination services. Moreover, in intensively managed agricultural landscapes, bee abundance—particularly wild bee species and numbers—declines sharply with increasing distance from source populations, and plant fruit set gradually decreases.

4.3 Nutrient Cycling

Forest fragmentation affects soil biotic community structure and function through complex causal cascades in plant-soil systems, ultimately influencing forest soil nutrient cycling and function. In organically managed fields or heterogeneous landscapes, increased landscape supplementation and compensation effects enhance soil fauna diversity, leading to faster decomposition rates. However, case studies on landscape heterogeneity effects on nutrient cycling and other ecosystem services remain scarce. Diekötter et al. found no significant differences in litter decomposition and soil fauna feeding activity across different landscape structures and field management practices in winter wheat fields, though the underlying mechanisms require further investigation. Landscape heterogeneity represents an important approach for reconciling agricultural production with ecological benefits without compromising agricultural output. In-depth research on mechanisms linking landscape heterogeneity to biodiversity and ecosystem services will enable future optimization of both ecological and economic benefits through landscape planning and agronomic management.

5. Future Research Perspectives

The importance of biodiversity and its ecosystem services for sustainable development of agricultural ecosystems is undeniable. Most studies confirm that compositional heterogeneity in agricultural landscapes promotes biodiversity. However, the effects of configurational heterogeneity across different agricultural landscapes on non-agricultural biodiversity require further investigation. For functional landscape heterogeneity based on different biological functional groups or species units, rational planning of agricultural cover type configurations is particularly important. Mechanisms underlying agricultural landscape heterogeneity effects on non-agricultural biodiversity, as well as the formation and maintenance mechanisms of ecosystem services in agricultural landscapes, represent urgent scientific questions for future research. These studies will provide theoretical support for constructing multi-scale sustainable agricultural landscapes and achieving sustainable development of agricultural landscape systems.

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