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Edge Effect Intensity in Agroforestry Ecotones Under Fire Disturbance Scale

Guohui Chen[a], Zhongliang Gao[b, *], Lianli Fu[c], Kaixun Dong[d], Xiaojie Ma[e], Na Li[f], Wenquan Cheng[g], Xiaohui Pu[h], Ming Zhou[i]

School of Civil Engineering, Southwest Forestry University, 650224, Kunming, China

[a]chenskrskr@163.com, [b]winalite@swfu.edu.cn, [c]2765874572@qq.com, [d]2561024838@qq.com, [e]2814117929@qq.com, [f]3450482867@qq.com, [g]3387679390@qq.com, [h]1279918531@qq.com, [i]3143714363@qq.com

*Corresponding Author: Zhongliang Gao (E-mail: winalite@swfu.edu.cn)

ABSTRACT

Edge effect is a key concept in ecology and biodiversity conservation, playing a vital role in studying ecological processes at the ecosystem and landscape scales. Drawing on the concept, mechanisms, and connotations of edge effects, this paper analyzes the impacts of fire disturbance on agro-forest ecotones from multiple angles. Six indicators, including the Shannon-Wiener index, Simpson index, Margalef index, Pielou evenness index, tree height, and average diameter of new shoots, are used to assess edge effect intensity. By examining how fire disturbance affects ecosystem structure, species composition, and functions, this study aims to quantify its impacts on biodiversity and ecological processes in agro-forest ecotones. The findings provide a scientific basis for ecological restoration, fire prevention strategies, and forest management, helping to mitigate fire risks and protect regional ecosystems and biodiversity.

KEYWORDS

Edge effect; Fire disturbance; Agroforestry ecotone; Biodiversity.

1. INTRODUCTION

The agro–forest ecotone belongs to the conceptual domain of ecological transition zones, within which cropland and forestland are interspersed spatially and overlap temporally. In the boundary regions between two or more distinct biogeographical communities, unique ecological phenomena emerge characterized by pronounced edge effects[1]. These zones represent ecologically sensitive and fragile areas where natural drivers and anthropogenic disturbances are most active, and they are among the regions most responsive to climate change [2].

The edge effect refers to significant changes in factors like species diversity and productivity at the interface of two or more ecosystems, driven by interactions of matter, energy, or geographical attributes[3]. Current research focuses on scale analysis, a core issue in modern ecology. Distinguishing spatiotemporal scales is fundamental, as proper comparison and evaluation require clear scales and suitable methods[4]-[5]. China's forest resource depletion has created extensive secondary forests adjacent to farmland and wasteland, making forest edges critical for material-energy exchange[6]. Studying edge effects is essential for understanding these dynamic interfaces.

Current research on the intensity of edge effects in agro-forest ecotones remains insufficient, particularly under the scale of fire disturbance. There is a lack of long-term monitoring data and unclear scale analysis. As human demands for natural resources grow, the interfaces between farmland and forest are increasingly affected by these changes.

Scholarly studies on edge effects, both domestically and internationally, are ongoing. For example, Wen Qingchun [7] analyzed forest-farmland edge effects, showing that biomass in the edge zones of agro-forest ecosystems exceeds that of adjacent communities. Clarifying the relationship between fire disturbance and edge effects can provide theoretical references for fire prevention, ecological restoration, and biodiversity conservation in these transitional areas.

2. FACTORS INFLUENCING EDGE EFFECTS

2.1. Latitudinal Variation

Willmer, Julian et al. [8] have shown that, owing to strong seasonal fluctuations in environmental conditions, high-latitude regions are more capable of retaining species and accommodating changes in edge habitats; they can also benefit from the supplementation of resources from adjacent land-use types[9]. In contrast, tropical communities are more sensitive to temperature variation, which may lead to reduced species richness at low-latitude edges. Consequently, temperate-zone edge communities often exhibit higher species richness.

2.2. Environmental Contrast

Willmer and colleagues[8]further found that high environmental contrast—such as marked structural differences between forest and surrounding land-use—tends to reduce edge species richness, because extreme shifts in conditions can limit the biological carrying capacity of the edge zone and result in species loss. Conversely, where contrast is low, complementary resource flows across the boundary help maintain species diversity[10].

2.3. Distance from the Edge

Grete T. et al. [11]reported that both species richness and relative abundance of rodents peak within the forest–grassland ecotone. They observed that rodent richness increases moving into the forest interior, but that this positive edge effect diminishes markedly beyond approximately 40 m from the edge. Thus, the beneficial influence of the ecotone on overall diversity and abundance does not extend beyond 10 m if the goal is to sustain maximal biodiversity.

3. METHODS FOR STUDYING EDGE EFFECTS

3.1. Edge-effect intensity

According to the measurement method designed by Wang Bo-sun et al.[12], suppose there is a quantitative index measuring population abundance and structure within a community. Let Y denote this index in the ecotone formed by m communities, and let yiyi (for i=1,2,…,m) denote the same index in each individual community. Define the edge-effect intensity as EE. The model is then formulated as:

$$E_i = \frac{mY_i}{\sum_{i=1}^{m} y_{ij}} - 1 \quad (1)$$

In this study, m denotes the two ecosystems that form the agro-forest ecotone, hence m=2. Using the above formula, one can calculate metrics such as species diversity and species richness.

For variables like mean tree height and branch length, measurements in the edge zone are compared against those in the core zone, and the edge-effect intensity is then computed according to Equation (2).

$$E_i = \frac{\bar{P}_{i,\text{edge}} - \bar{P}_{i,\text{core}}}{\bar{P}_{i,\text{core}}} = \frac{\bar{P}_{i,\text{edge}}}{\bar{P}_{i,\text{core}}} - 1 \tag{2}$$

In Equation (2), $\bar{P}_{i,\text{edge}}$ denotes the mean value of the ii-th metric in the edge zone, and Pi,core¯Pi,core denotes the mean value of the ii-th metric in the core zone.

When E=0, no discernible edge effect is present.

When E>0, the edge effect is positive.

When E<0, the edge effect is negative.

3.2. Species diversity index

Species diversity, as a key feature of community structure, along with the underlying causes of its spatial patterns, forms the foundation and core of species diversity research[13]. In-depth exploration of the relationship between sampling scale and species diversity helps us better understand community structure and its organizational mechanisms[14]. The Shannon-Wiener index is used to represent species diversity—a metric that reflects community diversity based on species richness and emphasizes relative species abundances. Its spatial variation weakens as the sampling scale increases[15]. The formula can be expressed as:

$$H = -\sum_{i=1}^{S} p_i \ln p_i \tag{3}$$

Or

$$H = 3.3219(\lg N - \frac{1}{N}\sum_{i=1}^{S} n_i \lg n_i) \tag{4}$$

H denotes the diversity index,S is the total number of species,pi is the relative abundance of the ith species in the community (e.g. number of individuals, biomass, or cover) as a proportion of total abundance,

3.3. Ecological Dominance Index

Species and groups in a community that significantly control energy flow and exert a strong influence on the environment of other species are referred to as ecological dominant species [16]. Ecological dominance is represented by the Simpson index, which measures the probability that two randomly selected individuals without replacement from a collection of N individuals belonging to s species belong to the same species. A higher probability indicates lower diversity in the collection. When the collection is treated as a complete population, the calculated D value is a strict population parameter free of sampling error[17]. The formula can be expressed as:

$$C = \sum_{i=1}^{s} (n_i/N)^2 \tag{5}$$

Or

$$C = \sum_{i=1}^{s} n_i (n_i - 1)/N(N-1) \quad (6)$$

In the formula, N is the sum of importance values of all species in the sample, and ni is the importance value of the ith species among the ss species.

C represents ecological dominance: 0 indicates infinite diversity, and 1 indicates no diversity. For ease of inspection or observation, we express ecological dominance as 1 − C. That is, the formula becomes:

$$C = 1 - \sum_{i=1}^{s} (n_i/N)^2 \quad (7)$$

Or

$$C = 1 - \sum_{i=1}^{s} n_i (n_i - 1)/N(N-1) \quad (8)$$

3.4. Margalef Index

The Margalef index is mainly used to assess species richness in ecological communities. The higher the value of this index, the greater the species richness—meaning more different types of organisms are present in the ecosystem, and its complexity and stability may be stronger[18]. Compared with some other species-diversity indices, the Margalef index places more emphasis on reflecting the number of species and is more sensitive to changes in species richness. The formula is:

$$R = (s-1)/\ ln\, N \quad (9)$$

3.5. Calculation of Edge Effect Intensity

By substituting Equations (3), (6), and (9) into Equation (1), the edge intensity can be calculated using the Shannon-Wiener index, Simpson index, and Margalef index. The resulting calculation formulas are as follows:

$$E_h = \frac{mH}{\sum_{i=1}^{m} h_i} - 1 \quad (10)$$

$$E_c = \frac{mC}{\sum_{i=1}^{m} c_i} - 1 \quad (11)$$

$$E_r = \frac{mR}{\sum_{i=1}^{m} r_i} - 1 \quad (12)$$

H and h_i denote the species diversity index for the overall and i-th community, respectively; C and c_i denote the species dominance index; R and r_i denote the species richness index.

3.6. Landscape Ecological Methods

Landscape ecology, a key approach for macro - ecological studies, gains enhanced scientific rigor with GIS technology. In ecotone research, using aerial remote - sensing images to build landscape databases via GIS software and analyzing landscape index changes reveals landscape structure, function, and development patterns, providing decision - making support for regional ecological management[19].

Using landscape indicators to quantify features clarifies ecotones' roles in ecosystem synergy. Additionally, GIS extracts specific data—e.g., Wen Qingchun[7] used NDVI from remote sensing to study biomass at the upper Minjiang River forest-farmland boundary, offering new ideas for ecotone research.

4. THE IMPACT OF FIRE DISTURBANCE ON EDGE EFFECTS

4.1. Species-Specific Responses to Fire Edges

Species-specific traits and resource requirements are key drivers of post-fire recovery and recolonization, and they may play a crucial role in determining species responses to fire edges[20]. Disturbance-adapted species are more likely to dominate in burned areas[21].

Small, less mobile species struggle to cross edge zones until necessary survival resources recover sufficiently. For example, gastropod species richness remains reduced for up to four years post-fire[22]. In contrast, agile large species like (Lynx canadensis) are confirmed to immediately occupy fire edges, where vegetation provides favorable conditions[23].

4.2. Coupling Mechanism Between Fire Disturbance and Edge Effects

Fire is a critical ecological process in terrestrial ecosystems, regulating their structure and function. Recent research has widely focused on fire’s ecological effects and its feedback mechanisms on climate[24]. Studies show areas with reduced fire - burned areas largely coincide with regions of woody plant invasion[25]. Some plant species have evolved strategies to resist and recover from fire, such as fire stimulating flowering and seed release[26]. This means changes in fire disturbance regimes—including introduction or exclusion can alter ecosystem community composition. Thus, fire disturbance is vital for maintaining biodiversity and habitats [27].

4.3. Fire Disturbance Alters Physical Environmental Gradients at Edges

Edge zones between agricultural and forested areas often exhibit strong microclimatic gradients, such as variations in temperature, humidity, wind speed, and light intensity.

4.3.1. Temperature Increase and Enhanced Heat Transfer

Fires release substantial heat, causing sharp local temperature increases—particularly affecting lower vegetation layers and soil surfaces. This resets pre-existing temperature gradients, subsequently impacting plant physiological processes and seed germination. According to Cathelijne R et al. [28], areas with lower fuel loads and fire intensities may suffer greater soil damage due to fire, with burn depth closely related to heat transfer efficiency.

4.3.2. Changes in Light Intensity

Fires result in the death or thinning of edge vegetation, transforming formerly shaded and moist forest edges into more open areas. Increased light intensity alters the distribution patterns of photosynthetic species and facilitates the rapid expansion of light-loving pioneer species in the edge zone.

4.3.3. Changes in Soil Properties

Forest fires can significantly affect the biological, physical, and chemical qualities of soil, reducing nutrient pools through mechanisms such as volatilization, oxidation, ash displacement, and erosion[29]. Akburak et al.[30] found that soil carbon content drops sharply in the short term after a fire. Raison et al.[31]reported that oxidative reactions during fires deplete nutrient pools, with marked reductions in nitrogen, phosphorus, and magnesium. Mataix-Solera et al.[32] observed that temperatures above 300 °C can destroy soil water repellency, severely impacting soil water cycling and erosion characteristics.

4.4. Fire Disturbance Expands and Reshapes Edge Spatial Patterns

Following fire events, transition zones in edge areas often extend further into forest interiors, significantly widening the original "edge width" and enlarging the spatial extent of edge effects.

4.5. Nonlinear Relationship Between Fire Intensity and Edge Effects

Studies have revealed a complex non-linear relationship between fire disturbance intensity and edge effects[33]. Fire disturbance intensity, including factors like fire temperature and burning duration, may exhibit a "threshold effect" or "inverted U-shaped response" in relation to edge effect manifestations. The "threshold effect" means edge effects only become pronounced when disturbance intensity exceeds a specific level, while the "inverted U-shaped response" indicates edge effects are most significant under moderate fire disturbance, weakening at both low and high intensity levels [34].

5. CONCLUSION

The edge effects in agro-forest ecotones under fire disturbance represent a complex issue involving ecology, landscape science, fire science, and environmental management. Through a comprehensive review of existing literature and research findings, we have gained a deeper understanding of how fire disturbance impacts ecological edges in agro-forest ecotones.

This paper focuses on the study of edge effects in agro-forest ecotones under the scale of fire disturbance. It elaborates on the influencing factors of edge effects, including latitudinal differences, environmental contrast, and distance from the edge. The calculation methods for edge effect intensity are introduced, which combine specific formulas with indices such as the Shannon-Wiener index, Simpson index, and Margalef index to quantify edge effects. By examining the impacts of fire disturbance on edge effects in ecotones, the research analyzes potential consequences of such disturbances.

Future research should emphasize long-term spatiotemporal data collection, multidisciplinary integration, and increased human intervention studies. These efforts will help assess the extent of fire disturbance impacts on biodiversity and ecological processes in agro-forest ecotones, providing a theoretical basis for formulating rational fire prevention measures, forest management strategies, and land use policies.

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