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# Vegetation Landscape Connectivity and Network Construction in Typical Riparian Buffer Zones of the Middle and Lower Reaches of the Yellow River: Postprint

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## Abstract

Vegetation serves as the foundation for the formation and maintenance of ecosystem services in riparian buffer zones, providing habitats and migration corridors for multiple species in terms of biodiversity conservation. Therefore, this study takes typical riparian buffer zone vegetation in the middle and lower reaches of the Yellow River as the research object, employing a combined methodology of remote sensing interpretation, landscape connectivity indices, patch importance evaluation, and corridor network analysis to examine changes in vegetation landscape connectivity and patch importance values in the study area for the years 2003, 2009, and 2015, and to construct a vegetation corridor network for riparian buffer zones, aiming to provide support for biodiversity conservation in riparian buffer zones of the middle and lower reaches of the Yellow River. The results indicate that the connectivity of vegetation patches in the study area exhibited an increasing trend from 2003 to 2015, and increased with increasing distance thresholds; under different distance thresholds, patch importance values increased with patch area and also increased with increasing distance thresholds; the importance values of small patches (0–5 $hm^2$) showed an increasing trend, those of medium patches (5–10 $hm^2$) displayed a trend of first increasing and then decreasing, while those of large patches (>10 $hm^2$) showed a decreasing trend. Vegetation corridor network analysis demonstrates that considering both important ecological nodes and ditch and road corridors can serve as an important reference for constructing vegetation corridor networks in the study area.

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## Full Text

# Landscape Connectivity and Network Construction of Riparian Vegetation in Typical Reach of the Middle and Lower Reaches of Yellow River

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### Abstract

Riparian ecosystems form critical linkages and exchange zones for matter, energy, and information between aquatic and terrestrial ecosystems, with their characteristics significantly influencing integrated landscape ecosystem functions. Riparian vegetation, as a key component of these ecosystems, provides the foundation for ecosystem service formation and maintenance in riparian buffer zones. However, riparian vegetation is widely recognized as a fragile and sensitive system requiring conservation due to strong disturbances and extensive alteration by anthropogenic activities globally. Conservation efforts have increasingly focused on restoring or creating natural areas to facilitate organism movement, often based on reliable measurements of landscape connectivity and patch importance. This study analyzed a typical riparian buffer zone in the middle and lower reaches of the Yellow River to assess landscape connectivity and the importance of riparian vegetation patches in 2003, 2009, and 2015 using remote sensing interpretation, landscape connectivity indices, patch importance evaluation, and corridor-network analysis. Additionally, we constructed a riparian vegetation corridor network to support biodiversity conservation in riparian buffer zones of the middle and lower Yellow River.

Our results indicated that landscape connectivity of riparian vegetation in-

creased both temporally from 2003 to 2015 and with increasing distance threshold. Specifically, the number of links (NL) and the number of patches in the largest component (NLC) increased over time and with greater threshold distances, while the number of components (NC) decreased. The integral index of connectivity (IIC) and probability of connectivity (PC) also increased with distance threshold. Under different threshold distances, patch importance values increased with patch area and generally increased with distance threshold. Importance values for small patches (0–5 $hm^2$) showed an increasing trend, medium patches (5–10 $hm^2$) exhibited an initial increase followed by a decrease, while large patches (>10 $hm^2$) showed a decreasing trend. Corridor network analysis demonstrated that considering important ecological nodes while simultaneously incorporating ditch and road corridors provides a crucial reference for constructing vegetation corridor networks in the study area.

**Keywords:** Riparian buffer zone; Vegetation; Landscape connectivity; Patch importance value; Vegetation corridor network; Middle and lower reaches of Yellow River

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## Introduction

Landscape connectivity examines the functional and ecological process linkages between patches of the same or different types [1-2]. It can quantify both the richness and rational distribution of patch types critical for species survival and support targeted strategies for landscape pattern enhancement and sustainable resource development [3], with applications spanning habitat maintenance, nature reserve construction, urban-rural environmental planning, and landscape regulation [4]. For example, Liang et al. [5] investigated road impacts on forest landscape connectivity in Gongyi City' s mountainous areas under different distance thresholds (reflecting resistance distances for species movement), finding that roads significantly constrained species activity and migration, negatively affecting forest landscape connectivity. Liu et al. [6] analyzed patch importance for landscape connectivity under various population dispersal distance scenarios before and after land consolidation, revealing that large patches and "stepping-stone" patches play crucial roles in maintaining ecological benefits. Zhang et al. [7] identified priority vegetation restoration areas through habitat connectivity analysis for Yunnan snub-nosed monkeys (*Rhinopithecus bieti*). Maguire et al. [8] examined tradeoffs in ecosystem services related to landscape connectivity for herbivorous insects, discovering that higher connectivity does not always benefit ecosystem services and may facilitate pest outbreaks. Additionally, some studies have addressed limitations in circuit theory and least-cost path methods for landscape connectivity assessment by proposing simple, individual-based alternatives such as "stochastic movement simulators" to improve calculation accuracy and rationality [9]. Research has primarily focused on nature reserves [10-11], road construction [5,12], slope farmland development [6], urban expansion [13], and wetland conservation [14], with relatively few studies addressing

riparian buffer zone vegetation landscape connectivity.

Riparian buffer zones represent ecotones between terrestrial and aquatic ecosystems, providing multiple ecosystem services, particularly in maintaining biodiversity by offering habitats and migration corridors for numerous species, making them hotspots of species richness [15-16]. As the foundation for ecosystem service formation and maintenance in riparian buffer zones, vegetation plays vital roles in controlling bank erosion, regulating temperature, filtering and retaining nutrients, purifying water quality, providing food and habitat for wildlife, and offering aesthetic and recreational resources [17-19]. However, influenced by natural factors (climate, channel morphology, bank structure, flood regimes, hydrodynamic characteristics) and anthropogenic factors (urbanization, agriculture, grazing, sand mining, water conservancy and hydropower development) and their interactions [17-18], riparian vegetation composition, structure, diversity, and spatial distribution patterns face severe disturbances [20], particularly regarding landscape connectivity degradation that affects corridor functions for species survival and migration. Therefore, investigating riparian buffer zone vegetation landscape connectivity is crucial for understanding vegetation corridor structure and ecosystem service maintenance [21]. The middle and lower reaches of the Yellow River represent important biodiversity conservation areas, including the Henan Xinxiang Yellow River Wetland Bird National Nature Reserve and the Zhengzhou Yellow River Wetland Nature Reserve (primarily located within the study area), which harbor rich flora and fauna resources, with 161 and 169 bird species respectively, and tens of thousands of migratory birds passing through, stopping, wintering, and breeding annually [22]. This study selected typical riparian buffer zone vegetation in the middle and lower Yellow River to analyze temporal changes in vegetation landscape connectivity and patch importance values, and to construct a vegetation corridor network based on corridor and network structure analysis, providing references for vegetation configuration and species conservation in this region.

### 1.1 Study Area

The study area is located in the transitional region between the middle and lower reaches of the Yellow River within Henan Province (34°48 -35°01 N, 113°03 - 114°30 E), extending from the Yiluo River estuary in the middle reaches to the Kaifeng Yellow River Bridge in the lower reaches, bounded by the north and south embankments of the Yellow River, covering four prefecture-level cities: Zhengzhou, Kaifeng, Xinxiang, and Jiaozuo [Figure 1: see original paper]. The area forms a continuous hilly-plain transitional landscape from west to east, with unique natural environmental characteristics [23]. Influenced by channel sedimentation, the Yellow River in this region has developed a typical wandering "elevated river" pattern [23], creating extensive riparian buffer zones that are constrained within embankments by water conservancy facilities, resulting in clear boundaries. The climate is warm temperate continental semi-humid monsoonal with north-south transitional features, with annual average temper-

atures of 12–16°C and annual precipitation of 550–650 mm, showing large interannual variation and uneven spatial distribution [23-24]. Dominant vegetation includes poplar (*Populus tomentosa*), willow (*Salix matsudana*), mixed plantations, and floodplain grasslands, with understory herbs primarily from Compositae, Gramineae, Leguminosae, and Brassicaceae families [24]. Soil texture is mainly sub-sandy and silt loam. Although most land has been cultivated, agricultural productivity remains low due to fragmented farming practices [23-24].

### 1.2.1 Landscape Classification and Ecological Patch Extraction

Based on three periods of winter Google Earth imagery from 2003, 2009, and 2015 (15 m resolution), and referencing current land use maps, we performed geometric correction and relative registration of remote sensing images using ENVI 5.1, with errors controlled within 0.5 pixels. Using digital line graphs, we extracted landscape type information through visual interpretation, classifying the study area into eight types: water body, farmland, forestland, grassland, floodplain, residential area, ditch, and pond, with hierarchical extraction of each type. Random sample verification based on 2014 field survey data of land use types and plant community distribution [24] achieved overall accuracy above 90%, meeting analytical requirements. Following relevant studies [5-6], grassland and forestland patches with high ecosystem service value were designated as ecological patches [Figure 2: see original paper], and landscape connectivity indices and patch importance values were calculated using ConeforSensinode 2.2 software.

### 1.2.2 Landscape Connectivity Index Calculation

Landscape connectivity represents the degree to which a landscape facilitates or impedes organism movement or ecological processes among patches [5]. Before calculating landscape connectivity with ConeforSensinode 2.2, the cumulative resistance distance threshold for vegetation patches must be determined. Cumulative resistance distance emphasizes the cumulative effect of landscape resistance over spatial distance [5-10]. When the resistance distance between two patches is less than or equal to the threshold, patches are considered connected; otherwise, they are disconnected. The maximum migration distance or activity range of conservation targets serves as an important reference for threshold determination. Drawing on previous research [5-6,10-11], average dispersal ranges of small and medium mammals and amphibians are 50–1,000 m, while average search ranges for birds are 30–32,000 m. Therefore, we established six thresholds (100 m, 500 m, 1,000 m, 2,000 m, 3,000 m, 4,000 m) to calculate landscape connectivity for ecological patches in 2003, 2009, and 2015, including number of links (NL), number of components (NC), number of patches in the largest component (NLC), integral index of connectivity (IIC), probability of connectivity index (PC), and importance values (dI) for different patch sizes to reflect connectivity patterns under various distance thresholds.

NL represents the specific number of connections between two different patches within the specified distance threshold. NC is a binary index (connected or disconnected) indicating the overall composition of functionally or structurally connected patches, with different landscape components isolated from each other and no ecological process connections between them. IIC represents overall connectivity, ranging between 0 and 1, where higher values indicate greater landscape connectivity and lower values indicate reduced connectivity; a value of 1 means all patches belong to the same landscape. The calculation formula is as follows [5-6]:

$$IIC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \frac{a_i \cdot a_j}{1+nl_{ij}}}{A_L^2}$$

where $n$ is the total number of patches in the landscape, $a_i$ and $a_j$ are the areas of patches $i$ and $j$ ($m^2$), $nl_ij$ is the number of shortest-path links between patches $i$ and $j$, and $A_L$ is the total study area (including both ecological and non-ecological patches).

PC represents the probability of connectivity index, ranging between 0 and 1, where higher values indicate greater landscape connectivity. A value of 1 means all patches belong to the same landscape, while 0 indicates no connectivity between patches. The calculation formula is:

$$PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i \cdot a_j \cdot p_{ij}}{A_L^2}$$

where patches $i$ and $j$ have multiple different paths, and $p_ij$ represents the maximum connection probability between them.

Patch importance value (dI) reflects the contribution of a specific patch to overall landscape connectivity. Different landscape connectivity indices yield different importance values. The dI value is calculated as:

$$dI = \frac{I - I_{remove}}{I} \times 100\%$$

where $I$ is the overall landscape connectivity when all patches are present, and $I_remove$ is the connectivity index value after removing a particular patch. Larger dI values indicate greater relative importance to the overall landscape. The dI calculation formula is universal across different connectivity indices. This study calculated patch importance based on the probability of connectivity index (PC) as follows:

$$dPC = \frac{PC - PC_{remove}}{PC}$$

where PC has the same meaning as $I$ in the previous formula.

### 1.2.3 Vegetation Corridor Network Construction and Structure Analysis

Networks are objective phenomena in natural and social systems, abstractly composed of nodes and corridors connecting them, where nodes represent different elements or locations in real systems and lines represent network extension or association degrees between nodes [10,12]. Ecological network construction includes various types such as road corridors, river corridors, and vegetation corridors. From a spatial perspective, this study constructed riparian buffer zone vegetation corridor networks through selection of vegetation nodes and corridors using different connection methods, and evaluated alternative network schemes through corridor structure and network structure analysis to select the optimal vegetation corridor network plan. Corridor structure characteristics were assessed using four metrics: number of nodes ($v$, where higher values indicate more vegetation patches concentrated in the network), number of corridors ($s$, where higher values indicate greater node connectivity), corridor length ($l$, the connection length between nodes), and corridor density ( , corridor length per unit area, where higher values indicate more complete network systems and better accessibility). Network characteristics employed four indices: circuitry index ( ), line-node ratio ( ), network connectivity ( ), and cost ratio (C).

The index describes the degree of loops in a network, representing the ratio of actual loops to maximum possible loops, ranging from 0 to 1. = 0 indicates no loops exist, while = 1 indicates maximum loop development. The calculation formula is [25]:

$$\alpha = \frac{s - v + 1}{2v - 5}$$

The index represents the average number of connections per node, serving as a simple measure of network complexity with a value range of 0–3. = 0 indicates no network exists, and increases with network complexity:

$$\beta = \frac{s}{v}$$

The index measures network connectivity, describing the degree to which all nodes are connected—the ratio of actual connecting corridors to maximum possible connections, ranging from 0 to 1. = 0 indicates no connections and only isolated points exist, while = 1 indicates every node is connected to all other nodes:

$$\gamma = \frac{s}{3(v - 2)}$$

While , , and indices measure abstract network properties, the C index incorporates corridor length to reflect network efficiency, where lower values indicate easier construction and implementation:

$$C = \frac{\sum_{i=1}^{s} l_i}{\sum_{i=1}^{s} l_{i,min}}$$

Network analysis data were based on 2015 vegetation data, constructing riparian buffer zone vegetation corridor networks through different approaches to adding vegetation patches.

## Results

### 2.1 Riparian Buffer Zone Vegetation Patch Characteristics and Landscape Connectivity Changes with Distance Threshold

As shown in [Figure 3: see original paper], the number of links (NL) among riparian buffer zone vegetation patches increased with distance threshold across all three periods, as larger thresholds facilitate easier establishment of connections between any two patches in the landscape. The number of components (NC) decreased with increasing distance threshold. At the 100 m threshold, NC was relatively high, indicating fragmented vegetation patches and low connectivity; at 500 m, NC increased annually, with the most pronounced fragmentation in 2003; at thresholds 1,000 m, NC differences among the three periods were minimal, suggesting similar patch aggregation degrees and high inter-patch connectivity. The number of patches in the largest component (NLC) increased with distance threshold. At 100 m, NLC showed an annual increasing trend, while its area initially increased then stabilized, accounting for 12.18%, 14.06%, and 14.06% of total patch area respectively. When distance threshold exceeded 2,000 m, NLC and its area proportion stabilized with increasing threshold. NC and NLC results suggest the optimal distance threshold for analyzing vegetation landscape connectivity in the study area should be within 2,000 m.

The integral index of connectivity (IIC) and probability of connectivity index (PC) directly reflect landscape structure dynamics. [Figure 3: see original paper] shows that IIC and PC increased from 2002 to 2009 and 2015, and increased with distance threshold. When distance threshold was <1,000 m, IIC and PC increased slowly, with 2009 showing the highest values across all three periods, while 2003 and 2015 values alternated. At thresholds >1,000 m, IIC and PC increased substantially, with IIC highest in 2009 and PC highest in 2015. These results indicate an inflection point at 1,000 m for vegetation landscape connectivity analysis in the study area.

### 2.2 Changes in Riparian Buffer Zone Vegetation Patch Importance Values

Patch importance values indicate each patch' s contribution to landscape connectivity under different distance thresholds, with higher values representing greater contributions.

As shown in , vegetation patches were dominated by large patches (>10 $hm^2$) with the largest area, followed by small patches (<5 $hm^2$), while medium patches (5-10 $hm^2$) had the lowest numbers and area. Patch numbers for all types increased from 2003-2015, with small and medium patch areas increasing annually while large patch areas decreased. Overall, larger patches had higher importance values, increasing from small to large patches. However, importance values gradually decreased from 2003 to 2015 for the same patch type. With increasing distance threshold, small patch importance values increased, medium patch values initially increased then decreased, while large patch values decreased. Standard deviation and coefficient of variation of importance values increased with patch area and showed similar trends to mean importance values with distance threshold, indicating that large patch importance values had high spatial variation due to patch location and surrounding small-medium patch numbers. All patch type importance values stabilized at the 1,000 m distance threshold.

### 2.3 Riparian Buffer Zone Vegetation Network Construction Based on Landscape Connectivity

Patches connected by corridors form networks. For riparian buffer zone ecological corridor network construction, this study considered patch spatial distribution, quantity, size, and shape factors. Based on 2015 patch importance values, we first classified network nodes by patch area and location, then constructed four vegetation network alternatives, and finally selected the optimal scheme by comparing corridor and network structure characteristics.

First, node classification identified important ecological nodes and general ecological nodes. Important nodes were large vegetation patches (>10 $hm^2$) with high ecological value in riparian buffer zones, primarily plantation forests. Based on patch area and importance values, we extracted 11 important nodes, 10 of which were distributed in embankment protection forests. General nodes were small vegetation patches near residential areas [Figure 4A: see original paper].

Second, based on vegetation corridor organization objectives and levels, we constructed four vegetation network alternatives using different connection methods [FIGURE:4B-4E]. Alternative 1 [Figure 4B: see original paper] connected only important ecological nodes, ignoring general nodes. Alternative 2 [Figure 4C: see original paper] considered both important and general nodes. Alternative 3 [Figure 4D: see original paper] incorporated road and ditch corridor conditions, enhancing connections among general nodes, important nodes, and corridors. The first three alternatives abstracted patches as nodes without considering connections between large patch edges and corridors. Therefore, Alternative 4

[Figure 4E: see original paper] treated large important vegetation patches separately, modified corridor connections from center points only, and adjusted node connections while considering ditch and road corridor orientations.

Finally, we selected the most suitable vegetation network by comparing corridor and network structure characteristics among alternatives. As shown in [Figure 5: see original paper], corridor node number ($v$) and corridor number ($s$) increased with network complexity across the four alternatives. Corridor length ($l$) and corridor density ( ), related to species habitat and material-energy exchange, were highest in Alternatives 3 and 4, indicating their superiority. Network structure characteristics showed Alternatives 1 and 2 had fewer loops, fewer connections per node, and lower node connectivity. Alternative 4 exhibited the highest network closure, most loops, greatest connections per node, and highest node connectivity, providing superior corridor connectivity favorable for energy and material cycling. Alternative 4 also had lower cost than Alternative 3, indicating easier implementation. Overall, Alternative 4 was optimal.

Based on this analysis, we connected important ecological nodes with corridors to form the main network framework, established diffusion networks by connecting general nodes to nearby important nodes and corridors, and created a comprehensive vegetation network system covering the entire region. The final construction scheme is shown in [Figure 6: see original paper].

## Conclusion and Discussion

Landscape connectivity measures the degree to which landscapes facilitate or impede movement among resource patches, widely applied in species conservation and landscape pattern optimization [3,8]. This study analyzed landscape connectivity and patch importance values under different thresholds for 2003, 2009, and 2015, constructed four vegetation network alternatives through node extraction, and identified the optimal vegetation network scheme considering important vegetation patches, ditch orientations, and road alignments through corridor and network structure analysis.

Vegetation landscape connectivity does not have a simple linear relationship with patch area but is influenced by different patch type compositions [10,26]. Our results show that patch importance values increase with patch area, but contributions of different patch types to landscape connectivity are affected by distance threshold. Large patch establishment enhances overall landscape connectivity—for example, although large vegetation patch numbers were lower in 2009 than 2015, large patch area, importance values, and IIC were higher in 2009, resulting in greater overall connectivity than in 2015. Small and medium patch establishment benefits probability of connectivity—for instance, small-medium patch numbers were greater in 2015 than 2009, and PC values exceeded 2009 levels when distance threshold increased sufficiently. Based on these results, vegetation network construction should prioritize connections between large patches while emphasizing the stepping-stone role of numerous small-medium patches

between large patches.

Previous studies often focused on specific species or populations, determining optimal resistance values based on landscape genetics, least-cost distance-gene flow relationships, and genetic heterogeneity, and identifying optimal distance thresholds by combining species-specific genetic characteristics, distribution patterns, and habitat area to provide conservation strategies [3,7-8,11]. Other studies examined human disturbance impacts on landscape connectivity in specific regions without targeting particular species, proposing biological conservation or landscape planning strategies based on connectivity responses [5-6,12-13]. However, research on riparian buffer zone vegetation landscape connectivity remains limited. As riparian buffer zones serve as biodiversity "sinks"[16] providing habitats and migration corridors for multiple species, and different species have varying migration and dispersal abilities, landscape connectivity studies targeting single species may contradict biodiversity conservation goals. Future research should analyze landscape connectivity for multiple species simultaneously and consider heterogeneity of ecological factors (elevation, temperature, precipitation) affecting species migration and dispersal to enhance practical significance.

Furthermore, riparian ecosystem functions depend on corridor length, width, internal habitat conditions, human activities, and location [21,27]. In the study area, vegetation is predominantly linearly distributed with insufficient width to create interior environments, numerous breakpoints cause corridor discontinuity, and the overall pattern consists of fragmented small-medium patches. Therefore, riparian buffer zone vegetation corridor construction should emphasize both corridor width and internal habitat complexity and its relationship with surrounding landscape units. It should be noted that the study area represents a relatively homogeneous agricultural landscape, so landscape connectivity calculations and patch component divisions were based on geometric distances between any two patches—patches were considered connected when distance was below the landscape threshold, without considering landscape matrix heterogeneity or assigning resistance coefficients to different landscape units [28].

Our results demonstrate that vegetation patch connection numbers and largest component patch numbers increased from 2003–2015 and with distance threshold, with connection numbers increasing substantially when threshold exceeded 1,000 m and largest component numbers stabilizing beyond 2,000 m. The number of components decreased over time and with threshold, stabilizing at 1,000 m. IIC and PC directly reflect landscape structure dynamics, increasing with threshold and showing substantial increases beyond 1,000 m. Patch importance values increased with patch area and threshold, with small patch importance increasing, medium patch importance showing initial increase then decrease, and large patch importance decreasing, all stabilizing at the 1,000 m threshold. Overall, 1,000 m represents the optimal distance threshold for analyzing vegetation landscape connectivity in the study area. Network construction using different connection methods demonstrated that establishing vegetation network frameworks through important ecological nodes and corridors while considering

ditch and road orientations creates systems with high corridor node numbers, network closure, and connectivity, providing methodological guidance for vegetation corridor network construction in the study area.

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