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, as the foundation for the formation and maintenance of ecosystem services in riparian buffer zones, provides habitats and migration corridors for various species in biodiversity conservation. Therefore, this study focuses on typical riparian buffer zone vegetation in the middle and lower reaches of the Yellow River, employing an integrated approach of remote sensing interpretation, landscape connectivity metrics, 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, thereby providing 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, which also increased with larger distance thresholds. Under different distance thresholds, patch importance values increased with patch area and also increased with the increase of distance thresholds. Specifically, the importance values of small patches (0-5 hm^2) showed an increasing trend, those of medium patches (5-10 hm^2) displayed a pattern of initial increase followed by decrease, while those of large patches (>10 hm^2) demonstrated a decreasing trend. Vegetation corridor network analysis revealed that considering both ditch and road corridors based on important ecological nodes can serve as a crucial reference for constructing vegetation corridor networks in the study area.

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 the linkages and exchange zones of matter, energy and information between aquatic and terrestrial ecosystems. The characteristics of such zones significantly influence integrated landscape ecosystem functions from land to riparian regions. Riparian vegetation as an important component of riparian ecosystem, is the basis of the formation and maintenance of riparian buffer zone ecosystem services. However, riparian vegetation has now been widely recognized as fragile and sensitive system requiring conservation as it undergoes strong disturbances and great alteration by anthropogenic activities globally. Conservation activities have largely focused on the restoration or creation of natural areas to facilitate the movement of organisms. This is often based on reliable measurement of landscape connectivity and patch importance. In this study, a typical riparian buffer zone in the middle and lower reaches of Yellow River was analyzed for landscape connectivity and importance of riparian vegetation in 2003, 2009 and 2015 using remote sensing, landscape connectivity indexes, patch importance evaluation and corridor-network analysis. Also the study constructed a riparian vegetation corridor-network in order to provide support for maintaining biodiversity in riparian buffer zones in the middle and lower reaches of Yellow River. The results indicated that landscape connectivity of riparian vegetation increased both from 2003 to 2015 and with increasing threshold distance. Thus the number of links (NL) and the number of the largest component (NLC) of vegetation patches increased from 2003 to 2015 and they increased with increasing threshold distance. However, the number of components decreased from 2003 to 2015 and with increasing threshold distance. The integral index of connectivity (IIC) and the probability of connectivity (PC) increased with increasing threshold distance. Under different threshold distances, the importance value increased with increasing patch area. Thus with increasing threshold distance, the importance value of small patches (0-5 hm^2) increased gradually, that of middle patches (5-10 hm^2) initially increased and then decreased, while those of large patches (>10 hm^2) decreased gradually. When the threshold distance was more than 1 000 m, the importance values of small, middle and large patches became stable, indicating that 1 000 m was the optimal threshold distance for the analysis of landscape connectivity in the study area. Ultimately, the corridor-network analysis proved to be important reference for the construction of riparian vegetation corridor-network. It simultaneously considered important ecological nodes, ditches and road corridors in the study area as the established vegetation network system had high corridor node number, network closure and connection degree. In addition, riparian vegetation corridor-network construction should not only prioritize the connection between large patches, but also emphasize the stepping-stone role of small and middle patches between the large patches.

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

Landscape connectivity explores the organic linkages between patches of the same or different types in terms of functional and ecological processes [1-2]. It can quantify both the richness of patch types crucial for species survival and the rationality of their distribution, while also facilitating targeted strategies for landscape pattern enhancement and sustainable resource development [3]. Landscape connectivity has been widely applied in practical fields such as habitat maintenance, nature reserve construction, urban-rural environmental planning, and landscape regulation [4]. For example, Liang et al. [5] examined the effects of roads on forest landscape connectivity in Gongyi City' s mountainous areas under different distance thresholds (reflecting resistance distances for species movement between patches), finding that roads significantly constrained species activities, hindered migration, and negatively impacted connectivity formation in forest patches. Liu et al. [6] analyzed the importance of habitat patches for landscape connectivity under different population migration and dispersal distance thresholds before and after land consolidation, revealing that large-area 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 the Yunnan snub-nosed monkey (*Rhinopithecus bieti*). Maguire et al. [8] investigated the trade-offs between positive and negative effects of landscape connectivity on forest ecosystem services using herbivorous insects as study objects, 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 approaches for landscape connectivity assessment by proposing a simple individual-based alternative method—the "stochastic movement simulator" —to improve calculation accuracy and rationality [9]. Research objects have primarily involved nature reserves [10-11], road construction [5,12], sloping farmland development [6], urban construction [13], and wetland protection [14], while studies on riparian buffer zone vegetation landscape connectivity remain scarce.

Riparian buffer zones are regarded as ecotones between terrestrial and aquatic ecosystems, providing multiple ecosystem services. Particularly in biodiversity maintenance, they serve as hotspots of species richness by offering habitats and migration corridors for numerous species [15-16]. As the foundation for formation and maintenance of riparian buffer zone ecosystem services, 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 cycles, river hydrodynamic characteristics) and anthropogenic factors (urbanization, agriculture, grazing, sand mining, water conservancy and hydropower development) as well as their interactions [17-18], the composition, structure, diversity, and spatial distribution patterns of riparian vegetation face severe disturbances [20]. Consequently, landscape connectivity that facilitates corridor functions (species survival and migration) has degraded seriously. Therefore, investigating riparian buffer zone vegetation landscape connectivity is crucial for understanding vegetation corridor structure and maintaining ecosystem services [21]. The middle and lower reaches of the Yellow River riparian buffer zone represent important biodiversity conservation areas, such as the Henan Xinxiang Yellow River Wetland Bird National Nature Reserve and Zhengzhou Yellow River Wetland Nature Reserve (primarily located within the study area), which harbor rich flora and fauna resources including 161 and 169 bird species respectively, with tens of thousands of migratory birds passing through, stopping, overwintering, and breeding annually [22]. This study selected typical riparian buffer zone vegetation in the middle and lower reaches of the Yellow River to analyze vegetation landscape connectivity and patch importance values across different periods, and to construct a vegetation corridor network based on corridor and network structure analysis, aiming to provide 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 southern and northern Yellow River dikes, 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 and from middle to lower reaches, featuring unique natural environmental characteristics [23]. In this region, the Yellow River has developed a typical wandering "suspended river" above ground due to sediment deposition [23], creating extensive riparian buffer zones that are constrained within the dikes by water conservancy facilities, resulting in clear boundaries. The climate is warm temperate continental semi-humid monsoon with north-south transitional features, with annual average temperatures 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. Most land has been cultivated, but agricultural productivity remains low due to fragmented farming [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, ENVI 5.1 was used for geometric correction and relative registration of remote sensing images with related maps, with errors controlled within 0.5 pixels. Using digital line graphs, visual interpretation was employed to extract landscape type information. The study area was classified into eight landscape 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 landscape classification and referencing relevant studies [5-6], grassland and forestland patches with high ecosystem service value were designated as ecological patches [Figure 2: see original paper]. ConeforSensinode 2.2 software was then used to calculate connectivity indices and patch importance values.

1.2.2 Landscape Connectivity Index Calculation

Landscape connectivity refers to the degree to which a landscape facilitates or impedes the movement of organisms or ecological processes among patches [5]. Before calculating landscape connectivity using Conefor Sensinode 2.2, the cumulative resistance distance threshold for vegetation patches must be determined. Cumulative resistance distance emphasizes the cumulative effect of landscape resistance across spatial distances [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 from previous research [5-6,10-11], average dispersal ranges of small-medium mammals and amphibians/reptiles are 50–1 000 m, while average search ranges for birds are 30–32 000 m. Therefore, this study set six thresholds: 100 m, 500 m, 1 000 m, 2 000 m, 3 000 m, and 4 000 m to calculate landscape connectivity [represented by number of links (NL), number of components (NC), number of patches in the largest component (NLC), integral index of connectivity (IIC), and probability of connectivity (PC)] and patch importance values (dI) for different area patches across the three years, reflecting landscape connectivity patterns under different distance thresholds. NL represents the specific number of connections between two different patches within the specified distance threshold. NC is a binary index (connected/unconnected) indicating the overall composition of structurally or functionally connected patches, with different landscape components being isolated from each other and lacking ecological process linkages. IIC represents overall connectivity, ranging between 0 and 1, where higher values indicate greater connectivity and lower values indicate less connectivity; a value of 1 means all patches belong to the same landscape. The calculation formula is as follows [5-6]:

Where *n* represents the total number of patches in the landscape, *i* and *j* are the areas of patch *i* and patch *j* (m^2), *nlij* is the number of shortest path connections between patch *i* and patch *j*, and *AL* 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 connectivity. A value of 1 means all patches belong to the same landscape, while 0 indicates no connectivity between patches. The calculation formula is:

Where between two patches *i* and *j* there are multiple different paths, *Pij* represents the maximum connection probability among them.

Patch importance value (dI) reflects the degree of importance of a particular patch to overall landscape connectivity or its contribution to maintaining landscape connectivity. Different landscape connectivity indices yield different patch importance values. The calculation formula is as follows:

Where *I* is the overall landscape connectivity when all patches exist, and *Iremove* is the landscape connectivity index value after removing a certain patch. A larger patch dI value indicates greater relative importance to the overall landscape, while a smaller value indicates lower importance. The dI calculation formula for different landscape connectivity indices is universal. This study calculated patch importance based on the probability of connectivity index (PC) using the following formula:

Where PC has the same meaning as *I* in formula (3).

1.2.3 Vegetation Corridor Network Construction and Structure Analysis

Networks are objective phenomena in natural and social systems. Abstractly, a network consists of many nodes and corridors connecting them, where nodes represent different elements or locations in real systems, and lines represent network extension or degree of association between nodes [10,12]. Ecological network construction includes different 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 various network schemes through corridor structure and network structure analysis to select the optimal vegetation corridor network plan. Corridor structure characteristics were assessed using four indicators: number of nodes (*v*, where larger values indicate more vegetation patches concentrated in the network), number of corridors (*s*, where larger values indicate higher node connectivity), corridor length (l, the line length connecting nodes), and corridor density (, corridor length per unit area, where higher values indicate a more complete and accessible vegetation corridor network system). 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, with a range of 0–1. =0 indicates no loops exist, while =1 indicates maximum loop development. The calculation formula is as follows [25]:

$$= (s - v + 1) / (2v - 5) \qquad (5)$$

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

$$= s / v \qquad (6)$$

The index measures network connectivity, describing the degree to which all nodes are connected—the ratio of actual connecting corridors to maximum possible connecting corridors, with a range of 0–1. A value of 0 indicates isolated points without connections, while 1 indicates every node connects to all other nodes. The calculation formula is:

$$= s / 3(v - 2) \qquad (7)$$

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

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

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 obvious fragmentation in 2003; at thresholds of 1 000 m and above, NC differences among the three periods were minimal, suggesting similar patch aggregation degrees and high interconnection among ecological patches. 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 and proportion stabilized. NC and NLC results indicate that the optimal distance threshold for studying vegetation landscape connectivity in this 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 threshold was less than 1 000 m, IIC and PC increased slowly, with 2009 showing the highest values across the three periods and 2003 and 2015 alternating. When threshold exceeded 1 000 m, IIC and PC increased substantially, with IIC highest in 2009 and PC highest in 2015. These results indicate that 1 000 m represents an inflection point for analyzing vegetation landscape connectivity 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—higher values represent 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 of all types increased from 2003 to 2015, with small and medium patch areas increasing annually while large patch area decreased. Overall, larger patches had higher importance values, which increased from small to large patches. Comparing the same patch type across years revealed gradually decreasing importance values from 2003 to 2015. 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 patch importance values increased with patch area and showed similar trends to mean importance values with increasing distance threshold, indicating that large patches were more affected by their location and surrounding small-medium patch numbers, resulting in greater spatial variation in importance values. 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 started from spatial distribution, quantity, size, and shape factors of patches. Based on 2015 patch importance values, network nodes were first classified by rank according to patch area and location, then four vegetation network plans were constructed, and finally the optimal scheme was selected by comparing corridor and network structure characteristics among different plans.

First, node classification included important ecological nodes and general ecological nodes. Important ecological nodes were large vegetation patches (>10 hm²) with high ecological value in the riparian buffer zone, primarily artificial forests. Eleven important nodes were extracted based on patch area and importance value, with 10 distributed within dike protection forests. General ecological nodes were small vegetation patches near residential areas [Figure 4A: see original paper].

Second, based on vegetation corridor organization objectives and levels, four different connection methods were used to construct vegetation network plans [FIGURE:4B-4E]. Plan 1 [Figure 4B: see original paper] connected only important ecological nodes without considering general node connections. Plan 2 [Figure 4C: see original paper] considered both important and general ecological nodes. Plan 3 [Figure 4D: see original paper] incorporated road and ditch corridor conditions to enhance connections among general nodes, important nodes, and corridors. The first three plans abstracted patches as nodes without considering connections between large patch edges and corridors. Therefore, Plan 4 [Figure 4E: see original paper] separated large important vegetation patches, changed the corridor connection method from center points only, and adjusted node connections while considering ditch and road corridor directions.

Finally, the most suitable vegetation network construction scheme was selected through comparative analysis of corridor and network structure characteristics. As shown in [Figure 5: see original paper], corridor node number (v) and corridor number (s) increased with network complexity across the four plans. Corridor length (l) and corridor density ( ), related to species habitat and material/energy exchange, were highest in Plans 3 and 4, indicating these were superior among the four options. Network structure characteristics showed that Plans 1 and 2 had fewer network loops, fewer connections per node, and lower node connection degrees. Plan 4 had the greatest network closure, most loops, highest connections per node, and greatest degree of node interconnection, providing the highest corridor connectivity favorable for energy and material cycling. Plan 4 also had lower cost than Plan 3, reflecting easier construction and implementation. Overall, Plan 4 was optimal.

Based on this analysis, important ecological nodes and corridors were linked to form the main vegetation network framework, while general ecological nodes were connected to nearby important nodes and corridors to create a diffusion network, ultimately forming a comprehensive vegetation network system covering the entire region. The final construction scheme is shown in [Figure 6: see original paper].

3 Conclusions and Discussion

Landscape connectivity measures the degree to which a landscape facilitates or impedes movement among resource patches and is 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 plans by extracting nodes, and obtained an optimal vegetation network scheme considering important vegetation patches, ditches, and road directions based on corridor and network structure analysis.

Vegetation landscape connectivity does not have a simple linear relationship with patch area but is influenced by patch type composition [10,26]. According to this study, patch importance values increased with patch area, but contributions of different patch types to landscape connectivity were affected by distance threshold. Large patch establishment helped improve overall landscape connectivity—for example, although large vegetation patch numbers were lower in 2009 than in 2015, large patch area, importance value, and overall connectivity index were higher in 2009, resulting in greater overall connectivity. Small-medium patch establishment benefited probability of connectivity—for instance, small-medium patch numbers were greater in 2015 than in 2009, and the probability of connectivity index was higher in 2015 when distance threshold increased to a certain level. Based on these results, vegetation network construction in the study area should prioritize connections between large patches while emphasizing the stepping-stone role of numerous small-medium patches between large patches.

Previous studies have often focused on specific species or populations, obtaining optimal resistance assignments based on landscape genetics, least-cost distance-gene flow relationships, and genetic heterogeneity, and determining optimal distance thresholds by combining species-specific genetic characteristics, distribution patterns, and total habitat area, providing conservation strategies for particular species [3,7-8,11]. Other studies have examined impacts of specific anthropogenic disturbances on landscape connectivity without targeting particular species [5-6,12-13], proposing biological conservation or landscape planning strategies based on connectivity responses [4]. However, research on riparian buffer zone vegetation landscape connectivity remains limited. As a regional biodiversity "sink" [16], riparian buffer zones provide habitats and migration corridors for multiple species, but different species have varying migration and dispersal abilities. Landscape connectivity research and optimization strategies targeting single species may deviate from the original intention of species diversity conservation. Future research should simultaneously analyze landscape connectivity for different species and consider heterogeneity of ecological factors (e.g., elevation, temperature, precipitation) on species migration and dispersal to enhance practical significance.

Riparian buffer zone ecosystem functions are influenced by vegetation corridor length, width, internal habitat conditions, human activities, and location [21,27]. Vegetation in the study area is mostly distributed in strips, where insufficient width prevents internal environment formation and excessive breakpoints cause corridor discontinuity, resulting in fragmented small-medium patches. Therefore, riparian buffer zone vegetation corridor construction should emphasize both corridor width and internal habitat complexity as well as relationships 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—when distance was below the landscape threshold, patches were considered connected—without considering landscape matrix heterogeneity effects or resistance coefficient assignment for different landscape units [28].

This study demonstrated that vegetation patch connection numbers and maximum component patch numbers increased from 2003 to 2015 and with increasing distance threshold. Connection numbers increased substantially when distance threshold exceeded 1 000 m, while maximum component patch numbers stabilized beyond 2 000 m. The number of components decreased from 2003 to 2015 and with increasing threshold, showing minimal differences among the three periods at 1 000 m, indicating stability. IIC and PC directly reflected landscape structure dynamics, increasing with distance threshold and showing substantial increases beyond 1 000 m. Patch importance values increased with patch area under different thresholds. With increasing threshold, small patch importance values increased, medium patch values initially increased then decreased, and large patch values decreased, stabilizing for all categories beyond 1 000 m. Overall, 1 000 m should be the optimal distance threshold for analyzing vegetation landscape connectivity in this area. Network construction using different connection methods demonstrated that establishing vegetation network frameworks through important ecological nodes and corridors while considering ditch and road directions creates systems with high corridor node numbers, network closure, and connectivity, providing methodological references for riparian buffer zone vegetation corridor network construction.

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