HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

ECOLOGICAL CONNECTIVITY NETWORKS IN LUOHE REGION, CHINA AND IN BUDAPEST AGGLOMERATION AREA, HUNGARY

Guifang Wang

Budapest

2024

The PhD School

Name: **Hungarian University of Agriculture and Life Sciences**
Landscape Architecture and Landscape Ecology

Discipline: **Agricultural Engineering**

Head: **Dr. László Bozó**
University professor, DSc, MHAS
MATE Institute of Horticultural Sciences
Department of Water Management and Climate Adaptation

Supervisor(s): **Dr. Sándor Jombach**
Associate professor, Ph.D.
MATE Institute of Landscape Architecture, Urban Planning and Garden Art
Department of Landscape Planning and Regional Development

....
Approval of the Head of Doctoral School

....
Approval of the Supervisor(s)

TABLE OF CONTENTS

1. BACKGROUND OF THE WORK AND ITS AIMS

Habitat fragmentation and habitat loss

Human activities result in habitat loss and fragmentation which are increasingly disrupting natural ecosystems (HADDAD et al. 2015, SAUNDERS et al. 1991) and wildlife populations (FAHRIG, MERRIAM 1994, WIENS 1995) across the world. Most researchers do not differentiate between habitat loss and habitat fragmentation when they measure fragmentation (FAHRIG 2003). In effect, landscape fragmentation and degradation cause habitat loss and impact the movement of species (CLOSSET-KOPP et al. 2016).

Habitat loss refers to the reduction of natural habitats or ecosystems influenced by human activities such as agriculture, urbanization, deforestation, resource extraction and so on, the natural habitats or ecosystems may not be capable to provide the food, water, and places for species' survival (NWF 2024, UGC 2024). Habitat loss can reduce the species richness (FINDLAY, HOULAHAN 1997, SCHMIEGELOW, MÖNKKÖNEN 2002, STEFFAN-DEWENTER et al. 2002, WETTSTEIN, SCHMID 1999), slow down the population growth rate (BASCOMPTE et al. 2002, DONOVAN, FLATHER 2002), and decrease the genetic diversity (GIBBS 2001) in biodiversity perspective. **Habitat fragmentation** is a landscape-scale, dynamic process (MCGARIGAL, CUSHMAN 2002) including both habitat loss and break apart of habitat (large, continuous of natural habitat patches are split apart into small, isolated fragments) (***Figure 1.1***) (FAHRIG 2003), is also a form of habitat loss. Generally speaking, habitat fragmentation and habitat loss can reduce landscape connectivity. Thus, maintaining landscape connectivity and mitigating habitat fragmentation may be critical for ecological processes such as gene flow, dispersal, and migration (RUDNICK et al. 2012). Therefore, ecological connectivity is the key way to preserving biodiversity, to reducing habitat fragmentation and safeguarding the species' survival.

Ecological Connectivity Networks

Ecological Connectivity Networks [1] (ECNs) can provide conservation solutions to mitigate the damage caused by intensified land use (JONGMAN 2008) by promoting landscape connectivity and reducing landscape fragmentation (UPADHYAY et al. 2017) through facilitating gene flow, migration, dispersal of species (RICOTTA et al. 2000). Therefore, an optimized ECN spatial pattern is of great significance for the sustainable development of urban and rural ecosystems

[1] Ecological Connectivity Networks: see the definition in 3.3

(RUIZ-GONZÁLEZ et al. 2014).

The increasing awareness of habitat fragmentation and landscape degradation has rapidly increased demand for modeling tools to simulate and evaluate ECNs. RUDNICK et al. (2012) illustrated modeling methods for evaluating landscape connectivity, and noted that Least-Cost Path (LCP)[2] (ADRIAENSEN et al. 2003) and UNIversal CORridor (UNICOR) cumulative resistant kernel[3] (COMPTON et al. 2007, LANDGUTH et al. 2012) analyses are some of the methods most frequently used to map ECNs (CUSHMAN et al. 2014, CUSHMAN et al. 2018, KASZTA et al. 2020a). Different input data from different methods generate different outcomes and meet diverse requirements to help planners in mapping ECNs and prioritizing protection priorities[4], which prompts researchers to explore the limitations and advantages of different modeling methods for assessing connectivity networks (e.g., RUIZ-GONZÁLEZ et al. 2014, ZELLER et al. 2018).

Goals

The goals in this dissertation are divided into two levels: regional level including Luohe region (LR) (***Figure 4.1***) and Budapest agglomeration area (BAA) (***Figure 4.4***) and central area level including Luohe central area (LCA) (***Figure 4.1***) and Budapest central area (BCA) (***Figure 4.4***). The main goals at regional level are to compare least-cost path analysis and UNICOR cumulative resistant kernel analysis frequently used in mapping ecological connectivity networks to explore the accessibility and applicability of these two methods, to assess the pattern of green network connectivity, and to rigorously prioritize the design of the ecological connectivity networks in species perspective and in spatial perspective. The main goals at the central area level are to explore the detailed information on ecological connectivity networks, and to rank the protection priority in species perspective. I applied the UNIversal CORridor and network simulation model (UNICOR) (LANDGUTH et al. 2012) and least-cost path (LCP) analyses (including LCP analysis by cost path and LCP analysis by Linkage Mapper) to simulate, map and evaluate the ECNs for multi-dispersal scenarios in LR, China, where intensive construction activities over the past several decades have resulted in massive and rapid land use change and reduction in natural ecosystems and habitats. I used the same method in BAA, Hungary, where human activities have reduced the biodiversity of wildlife which resulted in habitat loss and fragmentation. I also applied UNICOR in LCA, and in BCA where the intensive residential areas are.

To provide this critical information, I have goals like below:

---

[2] Least-Cost Path: see detailed information in 3.9.3

[3] UNIversal CORridor cumulative resistant kernel: see detailed information in 3.9.4

[4] Protection priority: protection priority is to protect the critical green space based on the urgency and importance of green space.

(1) to compare the differences and similarities of mapping methods ("LCP analysis" and "UNICOR analysis") in the LR and BAA and the differences and similarities of ecological connectivity networks in the LR, BAA, LCA, and BCA.

(2) to explore the relationship between landscape connectivity[5] and landscape composition[6].

(3) to evaluate the landscape fragmentation in LR, BAA, LCA and BCA.

(4) to map and compare the connectivity (resistant kernels[7](RK)) and the wildlife pathways (factorial LCPs) at multi-dispersal scenarios in the LR, BAA, LCA, and BCA, and to explore the relationship between RK and factorial LCP.

(5) to develop optimized ecological networks in order to prioritize protection in species perspective in the LR, BAA, LCA, and BCA and in spatial perspective in the LR and BAA.

(6) to identify the high connectivity areas in LR and BAA.

(7) to explore and describe the relation between ECNs and linear landscape elements (water surfaces and roads) in the LR and BAA.

---

[5] Landscape connectivity: see the definition in 3.2

[6] Landscape composition: see the definition in 3.5

[7] Resistant kernel: see the definition in 3.9.4

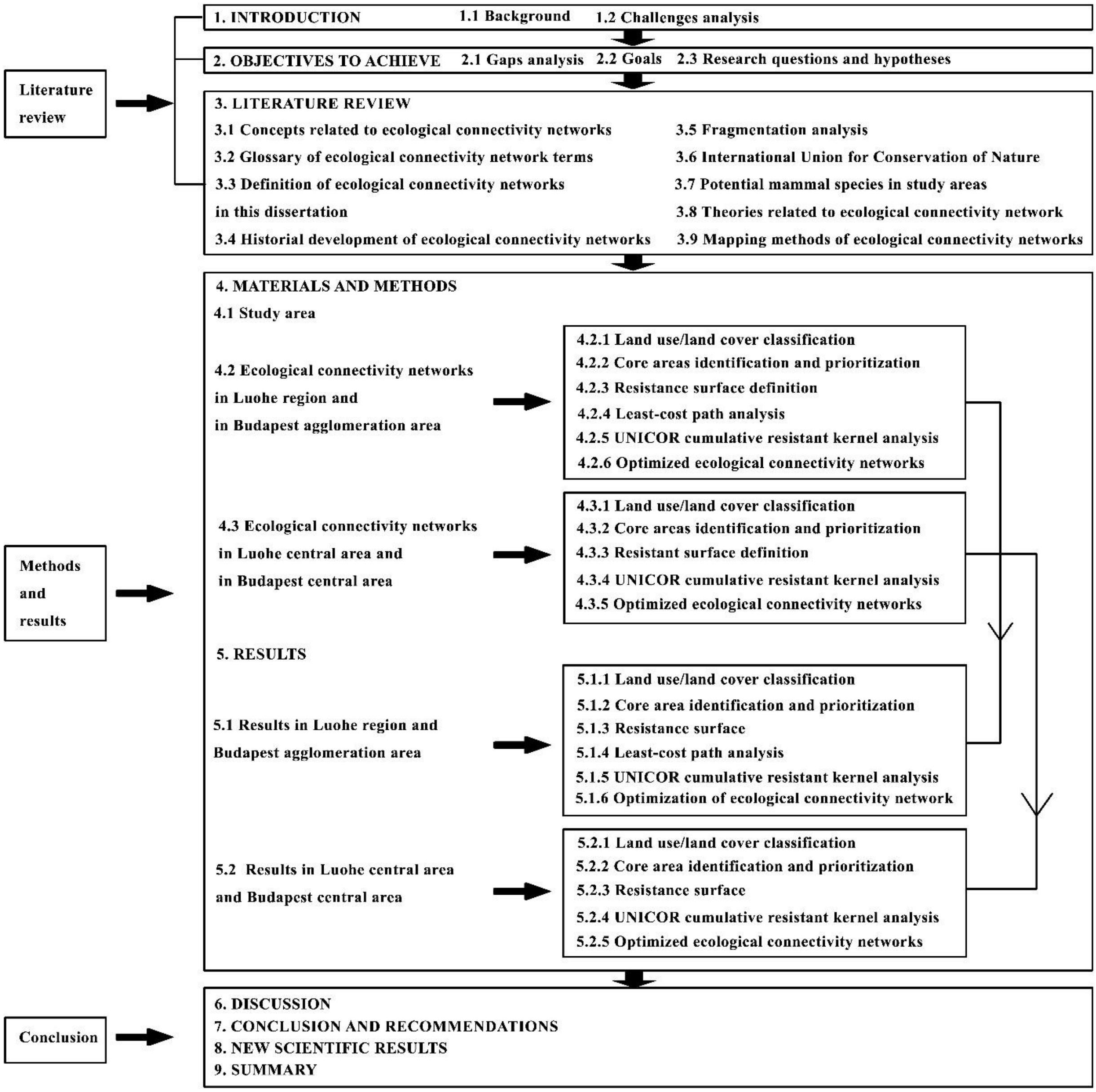


Figure 2.1: Framework of this dissertation

2. MATERIALS AND METHODS

The study areas include Luohe city in China and Budapest in Hungary. Luohe city includes two sub-level areas which are Luohe Region (LR) and Luohe Central Area (LCA), Budapest includes two sub-level areas which are Budapest Agglomeration Area (BAA) and Budapest Central Area (BCA).

Ecological connectivity networks in Luohe region and in Budapest agglomeration area

In this section, I used the big areas of study areas which are the Luohe region and the Budapest agglomeration area to map the ecological connectivity network (***Figure 4.7***). First, I used supervised classification to classify the land use/land cover (LULC) map for these two study areas. Second, I did a fragmentation analysis to quantify the landscape structure and composition. Third, I used two mapping methods called least-cost path analysis and UNICOR cumulative resistant kernel analysis to simulate the ECN (WANG et al. 2021, WANG et al. 2022). Finally, I optimized the ECN based on the results of the analyses I did in the last steps.

Methods in Luohe region and Budapest agglomeration area	
Land use classification	get land use/land cover map
Fragmentation analysis of land use/land cover map	analyse fragmentation degree of land use/land cover map
Core area identification	extract core areas from green space
Resistance surface definition	set the resistance for every land use type
Least-cost path analysis	get ecological connectivity networks without consideration of species limits
UNICOR cumulative resistant kernel analysis	get ecological connectivity networks with multi-dispersal scenarios
Analysis of resistant kernel modelling	define connected areas, and analyse fragmentation about them
Analysis of factorial least-cost path modelling	define meaningful paths, and analyse fragmentation about them
Optimization of ecological connectivity networks	recognize the highest connectivity areas
	rank protection priorities in species perspective
	rank protection priorities in spatial perspective
	analyse the relationship between corridors and roads & water surfaces

Figure 4.7: Methods in Luohe region and in Budapest agglomeration area

Ecological connectivity networks in Luohe central area and in Budapest central area

In this part, I used UNICOR cumulative RK analysis to simulate ECN with multi-dispersal scenarios in LCA and in BCA (***Figure 4.9***). I defined barriers, core habitat patches, and fracture zones for these two study areas. Meanwhile, I also identified low connectivity areas, medium connectivity areas, high connectivity areas, low connectivity paths, medium connectivity paths, and high connectivity paths for these two study areas. Finally, I ranked the protection priority in species perspective.

Methods in Luohe central area and Budapest central area	
Land use classification	get land use/land cover map
Fragmentation analysis of land use/land cover map	analyse fragmentation degree of land use/land cover map
Core area identification	extract core areas from green space
Resistance surface definition	set the resistance for every land use type
UNICOR cumulative resistant kernel analysis	get ecological connectivity networks with multi-dispersal scenarios
Analysis of resistant kernel modelling	recognize barriers, core habitat patches, and fracture zones, and analyse fragmentation about them
	sum value for kernels
	define the low, medium, high connectivity areas, and analyse fragmentation about them
Analysis of factorial least-cost path modelling	Sum value for the factorial least-cost paths
	define the low, medium, high connectivity paths, and analyse fragmentation about them
Optimization of ecological connectivity networks	rank protection priorities in species perspective

Figure 4.9: Methods in Luohe central area and in Budapest central area

3. RESULTS AND DISCUSSION

Luohe region.

The values of the RKs and the number and strength of paths increased rapidly with dispersal thresholds of ≤ 2 km, increased moderately with dispersal thresholds of 4 km and 8 km, and increased slightly with dispersal thresholds ≥ 16 km.

Budapest agglomeration area.

The values of the RK and the number and strength of paths increased dramatically with dispersal thresholds of ≤ 4 km, and increased slightly with dispersal thresholds ≥ 8 km.

Luohe central area.

The values of the RKs increased slightly with dispersal thresholds of ≤ 2 km, was moderate with dispersal threshold of 4 km, and increased rapidly with dispersal thresholds ≥ 8 km. The number of factorial LCPs stayed unchanged and strength of factorial LCPs increased slightly with dispersal thresholds of ≤ 2 km, was moderate with dispersal threshold of 4 km, and increased largely with dispersal thresholds ≥ 8 km.

Budapest central area.

The values of the RKs increased moderately with dispersal thresholds of ≤ 2 km, increased slightly with dispersal thresholds of 4 km and 8 km, and was the largest with dispersal threshold of 16 km. The number of factorial LCPs stayed unchanged, and the strength of factorial LCPs increased slightly with dispersal thresholds of ≤ 2 km, stayed unchanged with dispersal thresholds of 4 km and 8 km, and were the largest with dispersal threshold of 16 km.

Discussion

(1) The analysis produced here identifies the most critical, scale-dependent linkages among the main green-space core areas in the LR, BAA, LCA, and BCA and prioritizes them based on their importance. This analysis evaluated connectivity in a synoptic (CUSHMAN et al. 2014), scale-dependent (CUSHMAN et al. 2016) manner. Several recent research efforts have shown that scale-dependent synoptic analysis is critical to providing rigorous predictions of functional connectivity and evaluation of ECN (e.g., CUSHMAN et al. 2013c, 2014, 2016, 2018, KASATA et al. 2018, KHOSRAVI et al. 2018, ASHFRADZADEH et al. 2020). This is a strength of my analysis. I based my analysis on a classified land use map that was extremely accurate, which is also a strength. My analysis assumed expert values for the resistance of different land use classes, which is not ideal and may not reflect the actual resistance experienced by different organisms (e.g., MATEO-

SÁNCHEZ et al. 2015a, b, SHIRK et al. 2010, WASSERMAN et al. 2010, ZELLER et al. 2018). It would be desirable, therefore, to conduct empirical optimization of both the distribution and density of the source populations of species of interest (given the dominant effect this has on connectivity predictions; e.g., CUSHMAN et al. 2013b), the resistance of the landscape for their movement (e.g., CUSHMAN et al. 2006, CUSHMAN, LEWIS 2010), and their dispersal abilities (e.g., CUSHMAN et al. 2014, 2016). This would best be done through extensive biodiversity monitoring networks deployed across the green-space network (e.g., LUCID et al. 2018, 2019, 2021, ROBINSON et al. 2017), coupled with telemetry studies of dispersal in focal taxa (e.g., CUSHMAN, LEWIS 2010, ELLIOT et al. 2014) or landscape genetics (e.g., CUSHMAN et al. 2006, SHIRK et al. 2010, WASSERMAN et al. 2010, MATEO-SÁNCHEZ et al. 2015b, ZELLER et al. 2018). In the present, however, the current analyses provide a robust and informative assessment of the patterns of ECN connectivity in a synoptic, scale-dependent manner, enabling localization and prioritization of land use actions to enhance the extensiveness, strength, and resilience of the green space network in the LR, BAA, LCA, and BCA.

(2) The resolution of the Landsat 8 images I used is low. Higher-resolution satellite images do not necessarily provide a better land use classification (IRONS et al. 1985), but increase the internal variability within the same LULC type (CARLEER et al. 2005, CUSHNIE 1987, WOODCOCK, STRAHLER 1987, APLIN et al. 1997, THOMAS et al. 2003). This might reduce the accuracy of land use classification (IRONS et al. 1985) in LR and in BAA. In future research, I should employ high-resolution images to examine how image resolution affects land use classification results. I defined five classes of land use for general species in LR and in BAA, however, I will further specify green space types (e.g. forest, grassland, shrubland, orchard, urban green area) based on specific species in future in-depth research.

(3) Running UNICOR analysis requires a substantial amount of installed RAM. I currently have 128 GB of installed RAM, which can efficiently handle 17 core areas with 875 source points at a 100 m resolution in LR, and 23 core areas with 794 source points at a 200 m resolution in BAA. If analysis requires running data for additional core areas with higher resolutions, it is advisable to upgrade the installed RAM accordingly.

(4) Road coverage on OpenStreetMap. I applied the same filters for the road data in OpenStreetMap, but observed different road densities in LR (***Figure 4.3***) and in BAA (***Figure 4.6***). Two main reasons account for this disparity: 1) OpenStreetMap coverage is significantly better in BAA compared to LR. 2) Data availability on OpenStreetMap is much higher in BAA due to China's stringent national security concerns, restricting the capture of extensive data from China. Consequently, the intersection of LCP in LR is less accurate than the reality.

4. CONCLUSION AND RECOMMENDATIONS

Conclusion

(1) Cost-distance or cumulative resistance methods that do not account for source point distribution and density or the dispersal ability of the species are also very limited and potentially misleading. Resistant kernel modeling, such as those implemented in UNICOR, resolves the limitations of traditional cost-distance and cumulative resistance analysis by enabling explicit accounting for the influences of spatially varying distribution and density of the focal species population as well as the critical influences of its dispersal ability.

(2) The LCP analysis provided a simple and easy-to-understand illustration of potential paths connecting habitat patches, but grossly underpredicted areas where the species may be used for movement because the results only contained very narrow paths and lacked the consideration of species' dispersal limit. Factorial LCP analysis, such as those implemented in UNICOR, greatly improves the utility of LCP analysis by enabling it to account for the density and distribution of a source population and the dispersal ability of the species in predicting spatially synoptic patterns of ECN strength.

(3) The combination of factorial LCP and RK analysis jointly provides complementary and synergistic information that provides a strong suite of methods for comprehensive assessment of ECN extensiveness, effectiveness, and prioritization of landscape scenarios to optimize ECN in the future.

(4) RK analysis predicted the density of dispersal movement across the landscape, revealing that the extensiveness of kernel connectivity was highly dependent on dispersal ability. For small dispersal abilities of ≤ 2 km in LR, LCA, and BCA, and dispersal abilities of ≤ 4 km in BAA, high levels of fragmentation were observed. As dispersal ability increased, kernel connectivity produced broader extents of interconnected habitat.

(5) Factorial LCPs predict the routes of the highest potential connectivity linking all pairs of source points, revealing the optimal network of linkages among the source locations. Different dispersal abilities exhibit the same pattern of corridors, but the extent and connectivity of the network are highly sensitive to dispersal ability. Depending on dispersal ability, factorial LCPs in LR, BAA, LCA, and BCA do not connect all ecological nodes due to the high density of built-up areas. Factorial LCPs in LR pass through the LCA, and factorial LCPs in LCA eventually connect the west and northeast parts, thanks to the green spaces along the rivers. Factorial LCPs in BAA pass through the northwest part, where the mountain area is located. However, factorial LCPs in BCA face significant restrictions due to the high density of built-up areas.

Recommendations

(1) Recommendations in Luohe region

Species with dispersal abilities of ≤ 2 km which is the first-order conservation in species perspective were very vulnerable. In future planning, planners should consider species of short dispersal abilities and build stepping stones strategically across the region to enable linkage among the green space network to meet their biodiversity requirements, such as additional roadside green spaces, residential area green spaces, transport corridors, and river corridors.

Species with dispersal abilities of 4 km and 8 km which is the second-order conservation were moderately sensitive, planners should build parks or gardens in the areas where linkage is most limited between the core areas to protect species with medium dispersal abilities in future planning.

Species with dispersal abilities of ≥ 16 km, which is the third-order conservation could move smoothly in the study area extent, planners could choose a few conservation areas with complete ecosystem functionality to conserve long-distance dispersal species. Species with large dispersal ability, however, generally also have larger body sizes and lower population densities, so their ability to persist is likely limited by the small extent and generally small size of green space patches. For these species with high vagility but large habitat area requirements, conservation strategies should focus on increasing the extent of green space as much as possible with less concern about where it is located.

(2) Recommendations in Budapest agglomeration area

Species with dispersal abilities of ≤ 4 km which is the first-order conservation were very sensitive, planners should consider species of short dispersal abilities in northeastern, southeastern, and southwestern parts of the BAA and build small parks in these areas.

Species with dispersal abilities ≥ 8 km which is the second-order conservation would move smoothly in the northern part of the study area, planners should build parks or gardens in the southern and middle parts of BAA where linkage is most limited between the core areas and protected the existing high connectivity northern part of BAA to protect medium dispersal abilities' species in future planning.

(3) Recommendation of protection priority in spatial perspective in Luohe region and Budapest agglomeration area

First protection priority is very urgent and important to protect as most species pass through these areas, planners should firstly preserve these areas if there is a budget in urban planning. And then planners should preserve other areas based on the protection priorities correspondingly.

5. NEW SCIENTIFIC RESULTS

<u>Thesis 1: Different mapping methods resulted in different core areas, resistant surfaces, and corridors</u>

The LCP analysis provided a simple and easy-to-understand illustration of potential paths without the consideration of species limits; UNICOR analysis considered the species' limitations to model enriched information of corridors for multi-dispersal thresholds. **I have determined that UNICOR analysis is more suitable for the illustration of corridor strength which assesses the sections of pathways differently, pixel by pixel.**

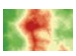
a) **Different source parameters (*Table 8.1*).** LCP analysis only takes into account resistance surfaces and core areas when predicting connectivity. In contrast, UNICOR analysis goes further by considering the distribution and density of the source population, as well as the dispersal limits of the species. This enhancement allows for the utilization of novel methodologies in analyzing ECN.

b) **Different resistance surface outcomes (*Table 8.1*).** The outcomes of resistance surfaces, including cumulative resistance surfaces and RKs, highlight how UNICOR analysis improves the understanding of connectivity by additionally considering the species' limitations. It provides a more detailed view compared to the LCP analysis.

c) **Different corridors (*Table 8.1*).** The analyses of LCPs and factorial LCPs provide a more comprehensive understanding of corridors by considering not just the spatial patterns but also the corridor strength. The extent and strength of the corridors for multi-dispersal thresholds add depth to the analysis.

Overall, these elements illustrate advancements in refining methodologies, understanding ecological connectivity, and offering a more detailed insight into corridors.

Table 8.1: Comparison of mapping methods (small Figures here from ***Figure 5.11, 5.12, 5.15***)

Comparison items	**LCP analysis by cost path**	**LCP analysis by Linkage Mapper**	**UNICOR**
Source parameter	The central point of core area polygon 	Core area polygon 	The set of source points of core area pixels 
Resistance surface outcome	Whole cost map (Cumulative resistance surface) 	Whole cost map (Cumulative resistance surface) 	Connectivity map (Resistant kernel) 
Corridor type	Raster corridor without corridor strength 	Vector corridor without corridor strength 	Raster corridor with corridor strength 

Thesis 2: Different ratios of the highest resistance surfaces (including built-up areas and roads) affected the whole landscape connectivity distinctly for species with different dispersal abilities, and also affected the ratio of low, medium, and high connectivity areas and low, medium, and high connectivity paths differently

The lower ratio of the impervious surfaces affected the whole connectivity largely, and the higher ratio of the impervious surfaces affected the whole connectivity intermediately. **I have defined that the different ratios of the highest resistance surfaces affected the whole landscape connectivity distinctly for species with different dispersal abilities, and also affected the ratio of low, medium, and high connectivity areas and low, medium, and high connectivity paths differently.**

a) **Impact of different ratios of the highest resistance surfaces on landscape connectivity between Luohe city and Budapest city.** The results reveal that in both Luohe City and Budapest City, a higher ratio of the highest resistance surfaces is associated with lower landscape connectivity. The ratio of the highest resistance surfaces in LR and BAA was lower than that in LCA and BCA, respectively. Correspondingly, the landscape connectivity in LR and BAA was higher than that in LCA and BCA at the same dispersal threshold. This proves that the higher the ratio of impervious surfaces, the lower the landscape connectivity. The summed values of RKs and factorial LCPs in the BCA are higher than that in the LCA with dispersal abilities ≤ 2 km, and the summed values of RKs and factorial LCPs in the LCA are higher than that in the BCA with dispersal abilities ≥ 4 km. This relationship is notably influenced by the ratio of built-up areas and roads, which is below 50% in LCA and above 80% in BCA.

b) **Impact of different ratios of the highest resistance surfaces on the ratio of low, medium, and high connectivity areas and low, medium, and high connectivity paths.** The ratio of low and high connectivity areas in the BCA was lower than that in the LCA with all the dispersal thresholds except medium connectivity areas with dispersal threshold of 1 km. The ratio of low, medium, and high connectivity paths in LCA was lower than that in BCA with dispersal thresholds ≤ 2 km. The ratio of low, medium, and high connectivity paths in LCA was higher than that in the BCA with dispersal thresholds ≥ 4 km.

In summary, the findings provide evidence about the complex interplay between the highest resistance surfaces and landscape connectivity, highlight the importance of considering urban characteristics (such as built-up areas and roads) when studying and planning landscape connectivity in urban environments.

Thesis 3: Landscape fragmentation largely affected landscape connectivity for species with different dispersal abilities

Landscape fragmentation decreased, and landscape connectivity increased with the dispersal thresholds increased. The number of connected areas and meaningful paths increased dramatically with short-dispersal abilities, and stayed stable with large-dispersal abilities. **I have defined that landscape fragmentation largely affected landscape connectivity for species with different dispersal abilities.**

a) **Relationship between landscape fragmentation and landscape connectivity in LR.** Values of PLAND, LPI, and GYRATE_AM of connected areas and meaningful paths increased dramatically with dispersal abilities of ≤ 2 km, these three values increased moderately with dispersal abilities at 4 km and 8 km, and these three values stayed unchanged with dispersal abilities ≥ 16 km.

b) **Relationship between landscape fragmentation and landscape connectivity in BAA.** The values of PLAND, LPI, and GYRATE_AM of connected areas and meaningful paths increased dramatically with dispersal abilities of ≤ 4 km, and these three values stayed unchanged with dispersal abilities of ≥ 8 km.

These conclusions collectively indicate how landscape fragmentation affects landscape connectivity among different species with multi-dispersal abilities in both the connected areas and meaningful paths. Lower dispersal abilities lead to fragmented and vulnerable connected areas and paths, while higher dispersal abilities result in highly connected areas and more aggregated paths. The fragmentation indices across different dispersal thresholds further enhance these findings, contributing to a better understanding of species movement and landscape connectivity.

<u>Thesis 4: The landscape connectivity defined the protection priority in species perspective</u>

Different species have different dispersal abilities, and the patterns of ECN are different for species with different dispersal abilities. **I have determined that species' dispersal ability defined the predictable connectivity of ECN, and the connectivity defined the protection priority in species perspective.**

> **Hierarchy of conservation prioritization based on the dispersal abilities in different regions.** Protection priority in species perspective only considers the species dispersal ability. Across these study areas, there's a consistent trend of categorizing species with short dispersal abilities ($\leq$ 2 km) as first-order conservation priorities. The hierarchy shifts based on the specific dispersal abilities observed in LR, BAA, LCA, and BCA, with higher dispersal abilities resulting in species being placed in second or third-order conservation priorities. The conservation prioritization hierarchy differs between regions, indicating that the conservation status in species perspective varies based on the local landscape context and the range of dispersal abilities observed in those areas.

These conclusions emphasize the importance of defining conservation strategies in species perspective within specific geographical regions. Understanding the hierarchical importance of conservation prioritization based on species' movement capacities aids in establishing effective conservation plans based on the unique characteristics of each area.

Thesis 5: The connectivity defined the protection priority in spatial perspective

LCPs illustrate the general spatial pattern of ECN, while factorial LCPs represent spatial pattern of ECN for species with different dispersal abilities. The determination of protection priorities in spatial perspective involves intersecting LCPs with factorial LCPs. **I have determined that the connectivity defined the protection priority in spatial perspective.**

The determination of protection priorities in spatial perspective takes into account not only the species' dispersal abilities but also the spatial pattern of ECN. Intersecting LCPs with factorial LCPs for species with short dispersal abilities results in the first protection priority. These networks are deemed the most crucial and urgent for addressing the spatial movement needs of species, as they are expected to be heavily utilized by a majority of species. On the other hand, LCPs alone, factorial LCPs alone, or the intersection of LCPs with factorial LCPs for species with large dispersal abilities result in the identification of second or third protection priorities. These networks are considered less important and less urgent to protect, as only a small number of species are expected to utilize them.

These conclusions highlight the establishment of protection priorities based on the usage of ECN in spatial perspective. It emphasizes the urgency and importance of protecting these identified networks, varying based on the expected species movement and the impact of different dispersal scenarios on their habitat utilization.

Thesis 6: The spatial arrangement of land use/land cover types significantly affected ecological connectivity networks and the highest connectivity areas

Corridors passed through the lowest resistance surface and avoided the highest resistance surface. The location of the highest connectivity areas was in the areas with the cluster of core areas. **I have defined that the location of the lowest resistance surface (core areas) and the highest resistance surface (built-up areas) significantly affected the spatial pattern of ecological connectivity networks and the spatial distribution of the highest connectivity areas.**

a) **The relationship between core areas & built-up areas and the spatial pattern of ECN.** In LR, core areas were evenly distributed throughout the entire area, while built-up areas were primarily concentrated in LCA, and in the northern and southwestern residential areas. Despite the high density of built-up areas in LCA, the LCPs traversed this area due to the presence of 25 core areas here, indicating the importance of these core areas for connectivity. In BAA, core areas were distributed around the edge of the area, and built-up areas were mainly located in BCA. However, despite the high density of built-up areas in BCA, the LCPs did not pass through this area due to the three core areas present there.
b) **The relationship between core areas & built-up areas and spatial distribution of highest connectivity areas.** In LR, the highest connectivity areas were concentrated in the Yancheng district. This spatial distribution correlates with the even distribution of core areas across the region, emphasizing their influence on connectivity. In BAA, the highest connectivity areas were located in the Pilis Mountains and Buda Hills. These areas exhibit the highest connectivity due to the natural landscape elements and the presence of core areas contributing to the connectivity.

These conclusions highlight the significant influence of core areas in facilitating connectivity, even in areas with high densities of built-up regions. They also emphasize the spatial disparities in ECN, which are influenced by the spatial distribution of core areas and built-up areas across the study areas.

Thesis 7: Linear elements of the landscape (water surfaces and roads) contributed to the spatial pattern of the ecological connectivity networks

After 1990, the Chinese government implemented policies aimed at improving ecosystem management and conservation, leading to the establishment of extensive green spaces along transportation and riparian corridors (PENG et al, 2017). These efforts contributed to shaping the landscape and potentially influenced the formation of ECNs. Budapest, as a capital city in the European Union, made substantial efforts to integrate local parks or gardens into the Pan European Ecological Network, indicating deliberate steps toward establishing a connected ECN within the city. The pattern of the intersection of LCPs with roads and water surfaces is the same with the pattern of LCPs in both the LR and the BAA. **I have determined that linear elements of the landscape (water surfaces and roads) contributed to the spatial pattern of the ecological connectivity networks.**

a) **Ratio of intersected LCPs with roads and water surfaces.** In LR, the ratio of intersected LCPs and roads (6.90%) was higher than that of intersected LCPs and water surfaces (6.13%). This suggests a relatively higher contribution of roads to the formation of LCPs in LR. However, in BAA, the contribution of roads to LCPs was significantly higher, with a much larger ratio of intersected LCPs and roads (54.62%) compared to water surfaces (5.02%). This highlights the dominant contribution of roads to the spatial pattern of ECN in BAA.
b) **Similarity between the intersection spatial pattern of LCPs with roads & water surfaces and general ECNs spatial patterns.** The spatial pattern observed in the intersection of LCPs with roads and water surfaces mirrors the overall spatial pattern of general ECNs (LCPs by Linkage Mapper) in both LR and BAA. This suggests that linear landscape elements contribute to the broader connectivity spatial patterns observed in the ECNs.

These conclusions indicate that governmental policies and deliberate urban planning efforts contribute to the establishment of ECNs, with linear landscape elements like roads significantly contributing to the formation of ECNs in study areas. The similarity between the intersection spatial pattern of LCPs with roads & water surfaces and general ECNs spatial patterns underscores their contribution to the overall ECNs within these landscape elements.

Thesis 8: Species' dispersal ability defined the resistant kernel connectivity, and factorial LCP connectivity had the same differences with resistant kernel connectivity

Species with small dispersal abilities had low kernel connectivity, while those with large dispersal abilities had high kernel connectivity. **I have determined that species' dispersal ability defined the resistant kernel connectivity, and factorial LCP connectivity had the same differences with resistant kernel connectivity.**

a) **Kernel connectivity and factorial LCP connectivity in LR and in BAA.** In LR, the values of the RKs increased rapidly with dispersal thresholds of ≤ 2 km, increased moderately with dispersal thresholds of 4 km and 8 km, and increased slightly with dispersal thresholds ≥ 16 km. Factorial LCPs had the similar change trend with the values of RKs, except they remained unchanged with the dispersal thresholds of ≥ 16 km in LR. In BAA, the values of RKs increased dramatically with dispersal thresholds of ≤ 4 km, and increased slightly with dispersal thresholds ≥ 8 km. Factorial LCPs had the similar change trend with the values of RKs, except they remained unchanged with dispersal thresholds ≥ 8 km. The ratio of connected areas and meaningful paths had the same differences with factorial LCPs both in LR and in BAA.

b) **Kernel connectivity and factorial LCP connectivity in LCA and in BCA.** In LCA, the values of the RKs increased slightly with dispersal thresholds of ≤ 2 km, was moderate with dispersal threshold of 4 km, and increased rapidly with dispersal thresholds ≥ 8 km. Factorial LCPs, and ratios of fracture zones, core habitat patches, low, medium, and high connectivity areas, and connectivity paths had the same differences with the values of RKs in LCA. In BCA, the values of the RKs increased moderately with dispersal thresholds of ≤ 2 km, increased slightly with dispersal thresholds of 4 km and 8 km, and was the largest with dispersal threshold of 16 km. Factorial LCPs had similar differences except they stayed unchanged with dispersal thresholds of 4 km and 8 km. The ratios of fracture zones, core habitat patches, low, medium, and high connectivity areas had the same differences with the values of RKs, and low, medium, and high connectivity paths had the same differences with factorial LCPs in BCA.

The analysis yielded several notable change trends within various scenarios regarding connectivity and dispersal abilities. It illustrates that resistant kernel connectivity increases with increasing dispersal abilities, and factorial LCP connectivity also increases alongside the resistant kernel connectivity.

6. LIST OF PUBLICATIONS

Journal paper

1. **WANG, G.**, CUSHMAN, S. A., WAN, H. Y., LIU, M., JOMBACH, S. (2022): Comparison of Least-cost Path and UNICOR Cumulative Resistant Kernel Analyses in Mapping Ecological Connectivity Networks in Luohe Region, China. In: *Journal of Digital Landscape Architecture*, 176-190. p.
2. **WANG, G.**, CUSHMAN, S. A., WAN, H. Y., LI, H., SZABÓ, Z., NING, D., JOMBACH, S. (2021): Ecological Connectivity Networks for Multi-dispersal Scenarios Using UNICOR Analysis in Luohe Region, China. In: *Journal of Digital Landscape Architecture*, 230-244. p.
3. **WANG, G.**, LI, H., YANG, Y., JOMBACH, S., TIAN, G. (2019): " City in the park," Greenway Network Concept of High-Density Cities: Adaptation of Singapore Park Connector Network in Chinese Cities. In: *Proceedings of the Fábos Conference on Landscape and Greenway Planning*, 6 (1) 13. p.
4. **WANG, G.**, MU, B., SONG, P., JIN, M., HE, R., TIAN, G. (2018): Scale effects on land use patterns in Luohe City based on an unmanned aerial vehicle survey. In: *Acta Ecologica Sinica*, 38 (14) 5158-5169. p.
5. LI, H., **WANG, G.**, TIAN, G., JOMBACH, S. (2020): Mapping and Analyzing the Park Cooling Effect on Urban Heat Island in an Expanding City: A Case Study in Zhengzhou City, China. In: *Land*, 9 (2) 57. p.
6. LI, H., **WANG, G.**, JOMBACH, S. (2020): Characteristics of winter urban heat island in Budapest at local and micro-scale. In: *Journal of Environmental Geography*, 13(3–4) 34–43. p.
7. LI, H., **WANG, G.**, TIAN, G., JOMBACH, S. (2019): Mapping and Assessment of the Urban Heat Island in Zhengzhou City. In: *Proceedings of the Fábos Conference on Landscape and Greenway Planning*, 6 (1) 38. p.
8. SZABÓ, Z., **WANG, G.**, SALLAY, Á. (2022): Estimating Solar Energy Potential of Hungary Based on Raster Maps. In: *Journal of Digital Landscape Architecture*, 112-123. p.
9. JOMBACH, S., LI, H., **WANG, G.**, VALÁNSZKI, I., KOVÁCS, K. F. (2019): Greenway Exploration in the Satellite Jungle: Discovery of Urban and Rural Green Network with Satellite Image Analysis in Hungary. In: *Proceedings of the Fábos Conference on Landscape and Greenway Planning*, 6 (1) 46. p.
10. LIU, M., SHI, Z., **WANG, G.**, YANG, Y., KOLLÁNYI, L. (2022): Comprehensive identification of ecologically important areas in Zhengzhou, China. In: *Proceedings of the Fábos Conference on Landscape and Greenway Planning*, 7(1):11. p.
11. LI, D., YANG, J., HU, T., **WANG, G.**, CUSHMAN, S. A., WANG, X., KOLLÁNYI, L., SU, G., YUAN, L., LI, B., WU, Y., BAI, T. The seeds of ecological recovery in urbanization – Spatiotemporal evolution of ecological resiliency of Dianchi Lake Basin, China. In: *Ecological Indicators*, 153 110431. p.
12. YANG, Y., HE, R., NING, D., **WANG, G.**, LIU, M., FEKETE, A. (2021): An Overview of Urban Park Development in Zhengzhou, China. In: *Acta Biologica Marisiensis*, 4 (2) 1-13. p.

13. BAI, T., WANG, X., CUSHMAN, S. A., YANG, J., **WANG, G.**, LÁSZLÓ, K., TIAN, G., HE, R., ZHANG, J., WANG, J., WU, Y. (2024): A neglected phenomenon: The spatiotemporal evolution of rivers in the city of Luohe, China. In: *Ecological Indicators*, 158 111323. p.

Conference paper

14. JOMBACH, S., VALÁNSZKI, I., LI, H., **WANG, G.**, KOVÁCS, K. F. (2019): Visualized relations of Land Use, Ecological Network and Heat Island: GIS based Analysis and Visualization in Hungarian pilot areas. In: *4th International Digital Landscape Architecture Conference*, 346. P.

15. LI, H., JOMBACH, S., BEN SALEM, S., **WANG, G.** (2021): A bibliometric review and illustration in urban heat island research from 1975 to 2020. In: *SZIEntific Meeting for Young Researchers 2020: ITT Ifjú Tehetségek Találkozója 2020*, 256-261. p.

Conference poster

16. LI, H., JOMBACH, S., BEN SALEM, S., **WANG, G.** (2021): A bibliometric review and illustration in urban heat island research from 1975 to 2020. In: *SZIEntific Meeting for Young Researchers 2020: ITT Ifjú Tehetségek Találkozója 2020*, 256-261. p.

Abstract

17. **WANG, G.**, CUSHMAN, S. A., WAN, H. Y., LIU, M., JOMBACH, S. (2022): Comparison of Least-cost Path and UNICOR Cumulative Resistant Kernel Analyses in Mapping Ecological Connectivity Networks in Luohe Region, China. In: *Journal of Digital Landscape Architecture*, 176-190. p.

18. **WANG, G.**, CUSHMAN, S. A., WAN, H. Y., LI, H., SZABÓ, Z., NING, D., JOMBACH, S. (2021): Ecological Connectivity Networks for Multi-dispersal Scenarios Using UNICOR Analysis in Luohe Region, China. In: *Journal of Digital Landscape Architecture*, 230-244. p.

19. **WANG, G.**, LI, H., YANG, Y., JOMBACH, S., TIAN, G. (2019): " City in the park," Greenway Network Concept of High-Density Cities: Adaptation of Singapore Park Connector Network in Chinese Cities. In: *Proceedings of the Fábos Conference on Landscape and Greenway Planning*, 6 (1) 13. p.

20. LI, H., **WANG, G.**, TIAN, G., JOMBACH, S. (2019): Mapping and Assessment of the Urban Heat Island in Zhengzhou City. In: *Proceedings of the Fábos Conference on Landscape and Greenway Planning*, 6 (1) 38. p.

21. SZABÓ, Z., **WANG, G.**, SALLAY, Á. (2022): Estimating Solar Energy Potential of Hungary Based on Raster Maps. In: *Journal of Digital Landscape Architecture*, 112-123. p.

22. JOMBACH, S., LI, H., **WANG, G.**, VALÁNSZKI, I., KOVÁCS, K. F. (2019): Greenway Exploration in the Satellite Jungle: Discovery of Urban and Rural Green Network with Satellite Image Analysis in Hungary. In: *Proceedings of the Fábos Conference on Landscape and Greenway Planning*, 6 (1) 46. p.

23. LIU, M., SHI, Z., **WANG, G.**, YANG, Y., KOLLÁNYI, L. (2022): Comprehensive identification of ecologically important areas in Zhengzhou, China. In: *Proceedings of the Fábos Conference on Landscape and Greenway Planning*, 7(1):11. p.