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Establishing an Ecological Network to Enhance Forest Connectivity in South Korea's Demilitarized Zone

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Abstract: This investigation delineated an ecological network within South Korea's Demilitarized Zone (DMZ) to enhance ecosystem functionality, with a focus on forest landscape connectivity. The study employed spatial autocorrelation analysis and the minimum cumulative resistance model to identify key source patches. These patches are vital for maintaining connectivity across various topographies and land uses in the DMZ. Morphological spatial pattern analysis in the DMZ's forest area showed a variation in forest patch types. The core class, less affected by external influences, was more prevalent in the eastern part. In contrast, the edge class, influenced by different environmental boundaries, was dominant in the western part. A 452.36 km long ecological network was constructed, serving as an essential corridor linking habitats of endangered species. This network covers a total forest area of 730.17 km^2, which includes an existing forest protection area of 165.84 km^2 (22.7%). The study also identified 564.33 km^2 (77.3%) of previously non-designated forest regions as potential conservation areas. This aims to significantly increase forest connectivity within the DMZ. The research highlights the effectiveness of spatial planning tools in promoting ecosystem integrity in politically sensitive and restricted-access areas.

Keywords: DMZ; ecological network; morphological pattern analysis; forest landscape connectivity; protected forest zone; spatial autocorrelation

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1. Introduction

In recent decades, the development-centric spatial planning paradigm has inflicted severe damage upon forest ecosystems across the globe. This harm primarily stems from habitat fragmentation, where a single habitat gets divided into numerous isolated segments [1,2]. Habitat fragmentation alters the structure and functioning of ecosystems, causing changes in environmental conditions such as light and wind, as well as disruptions in biological and non-biological flow dynamics across habitat patches [3]. Extensive research indicates that these intricate alterations ultimately lead to a decrease in biodiversity and ecological productivity. Persistent fragmentation has led to a situation where, as of 2015, around 20% of global forests are located within 100 m of a forest edge, and approximately 70% are within 1 km, posing a significant threat to the biodiversity of the world's forest ecosystems [1].

Ongoing research continues to uncover the adverse effects of habitat fragmentation on forest ecosystem structure and function [2,4–6]. Moreover, recognizing that most social and ecological processes impacting trees and forests occur within specific spatiotemporal landscape areas [7], forest management has shifted towards a landscape-focused approach [8]. This shift is evident in national and supranational efforts aimed at managing forests within the context of the larger landscape. For example, the United States and Europe have established national parks and the Natura 2000 network, respectively, as areas where forest ecosystems are legally protected and conserved. South Korea, for its part, designates 20 classes of protected areas, covering 17.2% of the country's total terrestrial area [9], in line with the United Nations Environment Programme's Aichi Target 11 [10]. This target

recommends conserving at least 17% of terrestrial and inland water areas and 10% of coastal and marine areas, especially those of significant biodiversity importance. However, as South Korea is a signatory to the Aichi biodiversity convention, it must also define additional protected areas to meet Post-2020 Global Diversity Framework Target 3, which sets a goal of conserving 30% of global land and sea areas by 2030 [11]. To achieve this, well-connected systems of protected areas must be designed, necessitating consideration of landscape connectivity. Landscape connectivity measures interactions that affect species migration, survival, gene flow, and the structure of the landscape, all of which are vital ecological processes [12]. Protecting landscape connectivity is, thus, a fundamental goal of ecosystem conservation [13–15].

A landscape-based ecological network consists of ecologically significant landscape segments that can contribute to biodiversity conservation [16]. Specifically, the forest patches play a core role in an ecological network as the structural connectivity of the forest patch is associated with its functional connectivity, such as genetic diversity, brought about by the potential migration of specific species [17,18]. Hence, when the structural connectivity of landscape elements is low or non-existent, the consequent deterioration of cause–effect relationships can damage ecological processes [19]. Considering this, strategies that increase the connectivity between forest patches with high and low landscape connectivity to enhance the ecosystem quality throughout the target area are expected to be useful approaches for managing forest landscapes [20,21].

Various theoretical approaches, including graph theory [22,23], source–sink theory [24,25], circuit theory [25–29], and habitat suitability theory [30], have been employed to establish ecological networks based on landscape connectivity. Notably, a recent approach combining morphological pattern theory [15] and graph theory [31] identifies core landscape elements influencing ecosystem connectivity [32,33]. This approach determines the minimum-cost path required to connect these elements, creating well-defined ecological networks that offer greater interpretive clarity than other methods [34–38]. Its practical applicability is particularly high for decision-making and planning.

This study aimed to establish an ecological network that enhances ecosystem function by promoting forest landscape connectivity. In particular, unlike previous studies that conducted global connectivity analyses to derive ecological network pathways [34–38], this study aimed to derive ecological network pathways that are effective in securing ecosystem connectivity in areas that are narrow and long, with distinct topographic and land use gradients. The study area encompassed the border region between South Korea and North Korea, where the absence of civilian activity after the Korean War allowed the forest ecosystem to recover towards its natural state [39–42]. The demilitarized zone (DMZ) in North Korea was excluded due to a lack of spatial data for analyzing forest landscape connectivity. Additionally, the DMZ's barbed-wire border restricts the movement of large terrestrial mammals. Our study identified critical forest source patches for preserving forest landscape connectivity, and we developed an effective ecological network by incorporating topographic and land use characteristics of the study area.

2. Materials and Methods

The analytical processes employed to establish the ecological network for forest landscape connectivity are summarized in Figure 1. Each analytical step is described in detail in the following sub-sections.

2.1. Study Area

The study area encompasses a portion of the border region between South Korea and North Korea, located within the geographical coordinates of 126°38′48.69″ E–128°24′42.6″ E and 37°49′40.31″ N–38°38′8.53″ N. This South Korean border region includes the Demilitarized Zone (DMZ), which is defined as the area situated 2 km south of the Military Demarcation Line (MDL), as per the Korean Armistice Agreement, effective since 27 July 1953. Additionally, the DMZ extends to within 10 km of the Southern Limit Line (SLL) of

the DMZ, forming the Civilian Control Zone (CCZ). The study area comprises portions of two administrative districts, Gyeonggi-do and Gangwon-do, one city (Paju-si), and six counties (Yeoncheon-gun, Cheorwon-gun, Hwacheon-gun, Yanggu-gun, Inje-gun, and Goseong-gun). For geographical accuracy, the study area was divided into four distinct regions: Paju (PJ), Yeoncheon (YC), Cheorwon (CW), and Gangwon (GW), which includes four counties: Hwacheon-gun, Yanggu-gun, Inje-gun, and Goseong-gun (Figure 2).

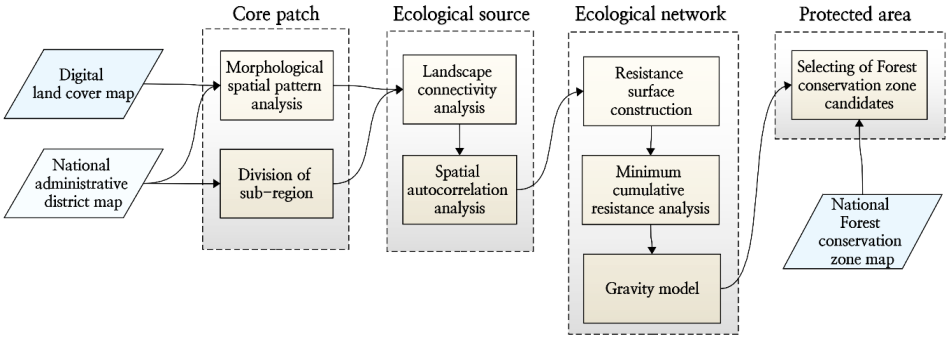


Figure 1. Flowchart outlining the study.

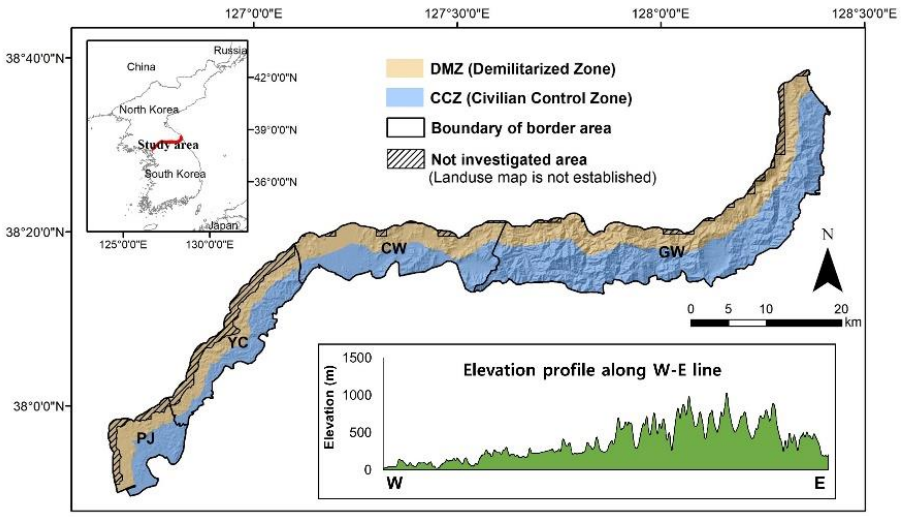


Figure 2. Map of the study area. The distribution per land use class is not shown on the map, according to the national security policy. The vertical cross-section of the study area was obtained from a shuttle-radar-topography-mission digital elevation model of a 30 m resolution (30 m SRTM DEM).

The study area exhibits an elevation range from 0 to 1216 m, characterized by an elevation pattern that inclines eastward and descends westward. The annual temperature within the region averages around 10.4 °C, with an average annual precipitation of approximately 1344.8 mm. Land use data for the study area are summarized in Table 1 and classified as follows: forest area was predominant at 70.96%, followed by agricultural area (9.08%) and grassland (6.64%). This distribution correlates with the topographical features, with higher elevations in the east and lower elevations in the west, resulting in a higher percentage of forested land in the eastern regions and a greater prevalence of land allocated for human activities, such as agriculture and urban development, in the western regions (Figure 3).

Deforestation attributed to military activities and forest fires has led to the wide distribution of vegetation, including grass, during the initial stages of secondary succession. Consequently, the ecological landscape is characterized by a simple structure primarily dominated by oak trees. In contrast, parts of the high-elevation eastern regions, where human activity is limited, feature old-growth forests [42].

Table 1. Land use classes in the study area (percentage of total area). Non-investigated indicates areas where investigation is prohibited for military purposes or due to the North Korean control of the territory. The units of area and percentage are km^2 and %, respectively.

Land Use Class	Area (Percentage)				
	PJ	YC	CW	GW	Total
Developed area	4.66 (2.27)	3.98 (1.18)	7.47 (1.82)	8.59 (0.81)	24.69 (1.23)
Agricultural area	44.19 (21.55)	39.50 (11.76)	73.93 (18)	24.89 (2.35)	182.50 (9.08)
Forest	73.34 (35.77)	163.27 (48.59)	250.77 (61.07)	938.76 (88.72)	1426.14 (70.96)
Grassland	22.24 (10.85)	38.91 (11.58)	47.20 (11.50)	25.18 (2.38)	133.54 (6.64)
Wetland	5.93 (2.89)	2.75 (0.82)	9.82 (2.39)	7.67 (0.72)	26.17 (1.30)
Bare ground	6.50 (3.17)	3.54 (1.05)	3.14 (0.76)	11.13 (1.05)	24.30 (1.21)
Water	12.73 (6.21)	3.70 (1.10)	6.62 (1.61)	4.99 (0.47)	28.05 (1.40)
Non-investigated	35.45 (17.29)	80.34 (23.91)	11.67 (2.84)	36.92 (3.49)	164.38 (8.18)
Total	205.03 (100)	336.00 (100)	410.61 (100)	1058.13 (100)	2009.77 (100)

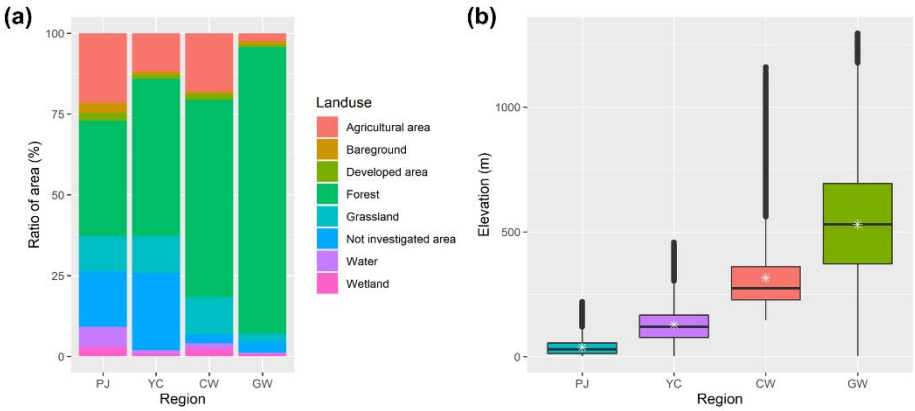


Figure 3. Ratio of land use class area by region (**a**) and elevation (**b**). Area for each land use class was estimated based on the 1:5000 land-cover map produced by the Korean Ministry of Environment in 2021, and elevation data were obtained from the 30 m SRTM DEM.

The presence of access restrictions and landmines in the border area has impeded in-depth investigations of its flora and fauna. Nonetheless, both the Korea Ministry of Environment and the National Institute of Ecology [43] have compiled published research on the area, reporting a total of 6373 species inhabiting the border region. Among these, 102 species are classified as endangered by the Korea Ministry of Environment, comprising 18 Class I species (e.g., *Urus thibetanus* ussuricus, *Naemorhedus caudatus*, *Moschus moschiferus*, *Grus japonensis*, and *Hyla suweonensis*) and 84 Class II species (e.g., *Pteromys volans* aluco, *Aegypius monachus*, and *Grus vipio*).

2.2. Identification of Ecological Sources

2.2.1. Morphological Spatial Pattern Analysis (MSPA)

To analyze the landscape morphology of the study area, a binary raster map at a 30 m spatial resolution classifying land use as foreground (forest) and background (non-forest) was generated using the 1:5000 m scale digital land vector cover map produced by the Korea Ministry of Environment in 2020 [44]. Map features were then reclassified into seven morphological categories: core (core habitat patch), islet (isolated small habitat patch), perforation (gap within a habitat patch), edge (boundary between different land covers), loop (ring-like habitat), bridge (connection between habitat patches), and branch (narrow habitat) [15] via the eight-neighborhood analysis method in the GuidosToolbox [45]. Lastly, core patches deemed critical for protecting landscape connectivity were extracted as ecological sources to analyze connectivity.

2.2.2. Evaluation of Landscape Connectivity

Regional patches critical for connectivity were extracted to prevent bias in selecting candidates for ecological sources and to adequately reflect the forest distribution with its higher density toward the east of the study area. The landscape connectivity for each core patch was calculated based on the delta of the probability of connectivity (dPC) index using the Conefor 2.6 software [46] for core patches extracted in the MSPA [31,36,37,47]. The following dPC equation was used [48]:

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1,i\neq j}^{n} P_{ij}^{*} a_i a_j}{A^2{}_L}, \; dPC = \frac{PC - PC'}{PC} \times 100\% \quad (1)$$

Here, a_i and a_j are the area of the i and j patches, respectively; A_L is the total area of the study region consisting of forest and non-forest areas; and P_{ij} is the link intensity indicating the direct probability of dispersal across patches i and j. The threshold value of the patch connectivity distance was established at 1000 m, and the connectivity probability was fixed at 0.5, as referenced in previous studies [36,49]. Regional patches critical for connectivity were extracted to prevent bias in selecting candidates for ecological sources and to adequately reflect the forest distribution with its higher density toward the east of the study area. The landscape connectivity for each core patch was calculated based on the delta of the probability of connectivity (dPC) index using the Conefor 2.6 software [46] for core patches extracted in the MSPA [31,36,37,47].

2.3. Constructing the Ecological Network

2.3.1. Area Clustering Using Spatial Autocorrelation Analysis

To construct an ecological network that can enhance forest landscape connectivity throughout the study area, a spatial autocorrelation analysis based on the landscape connectivity index was used to cluster forest areas and draw corridors to indicate paths connecting all clusters. Whether attribute values of a spatial variable at a specific location are significantly correlated with a nearby attribute could be verified with a spatial autocorrelation analysis [50]. The study area was divided into 500 m × 500 m meshes, and the mean connectivity index for the core forest patch in each mesh was estimated, with the aim of ensuring the structural stability of core forest areas unaffected by edge effects and securing the feasibility of spatial planning. In addition, the spatial aggregation characteristics of these meshes were analyzed by drawing a local indicator of spatial association (LISA) distribution map using the GeoDa software 1.20 [37,47,51,52]. LISA is an analytical technique employed to study localized spatial aggregation phenomena, whereby clusters of high attribute values (HH) and those of low attribute values (LL) can be identified for a set level of significance (p = 0.05). The HH outliers surrounded by LL clusters and LL outliers surrounded by HH clusters can also be identified [37,53]. Among the detected core patches in each HH and LL cluster identified from the analysis, those with the highest landscape connectivity index were selected as ecological source patches.

2.3.2. Constructing Ecological Cost and Ecological Resistance Surfaces

Raster-type ecological and resistance surfaces at a 30 m resolution were produced using methods suggested by Wanghe et al. [34]. The cost value of each patch was calculated according to the product of its weight and suitability score:

$$cost = 100 - weight \times suitability\ score \quad (2)$$

The efficiency of ecological network construction was improved by assigning high-weight values and suitability scores to land use classes with high ecosystem naturalness and by estimating the ecological cost per class (Table 2) [34]. For this estimation, the resistance, weight, and suitability coefficients utilized in this study were scientifically estimated based on a comprehensive review of the literature [34,54,55] and expert judgment in National Institute of Ecology, reflecting the relative importance and ecological impact of different

land use classes on forest connectivity. While previous studies have focused on creating networks of urban green infrastructure, this study assigns resistance values to a network of forest patches.

Table 2. Coefficients applied to estimate ecological cost and resistance.

Land Use Class	Weight	Suitability	Cost	Resistance
Developed area	0.05	100	95	100
Agricultural area	0.25	60	85	30
Forest	0.66	100	34	0.1
Grassland	0.3	80	76	0.5
Wetland	0.25	60	85	1
Bare ground	0.2	50	90	10
Water	0.1	10	99	1

2.3.3. Establishing the Ecological Network and Selecting Forest Area Candidates for Protection

Based on the constructed resistance surface, the minimum cumulative resistance (MCR) model was used to draw efficient corridors between core source patches. The MCR model comprised the following formula [36,56,57]:

$$mcr = f_{min} \sum_{j=n}^{i=m} (D_{ij} \times R_i) \quad (3)$$

Here, *mcr* is the resistance of the potential corridor connecting two patches; f is an unknown positive function that represents the minimum resistance at a specific spatial location, the distance to all sources, and the positive correlation across the landscape-based surfaces; D_{ij} is the distance from the source point j to the spatial unit i; and R_i is the resistance coefficient for the spatial unit i [36].

Among the candidate corridors extracted using the MCR model, the core corridor paths constituting the ecological network were selected using the gravity model tool of ArcGIS 10.7 [58]. The gravity model simulates interactions between nodes connected through the corridors: more interactions indicate a higher significance of corridor connectivity. The equation outlining the gravity model is as follows [34]:

$$G_{ab} = \frac{N_a N_b}{D^2_{ab}} = \frac{L^2_{max} \times S_a \times S_b}{L^2_{ab} \times p_a \times P_b} \quad (4)$$

Here, G_{ab} is the interaction between nodes a and b; N is the weight on the corresponding node; D_{ab} is the standardized resistance value of the potential corridor for nodes a and b; and S and P indicate the area and resistance of the corresponding node, respectively. The resistance value of a patch is defined according to its land use class, which is associated with the level of difficulty in constructing the given ecological corridor. L_{ab} is the cumulative resistance of the corridor for nodes a and b; L_{max} is the maximum resistance across all corridors in the study area.

Lastly, from potential corridors connecting core source areas at each cluster derived from the MCR model, corridors with the highest interaction values were selected to construct an ecological network. In addition, forests in areas where a network passed but was yet to be designated as a forest conservation zone were selected as protection-area candidates.

3. Results

3.1. Ecological Sources

Figure 4 shows the distribution of each landscape class following reclassification in the MSPA. The ratio of core classes throughout the study area accounted for the widest area at approximately 62%. The core area ratio in each region increased toward the east, while that of the edge area increased toward the west (Table 3).

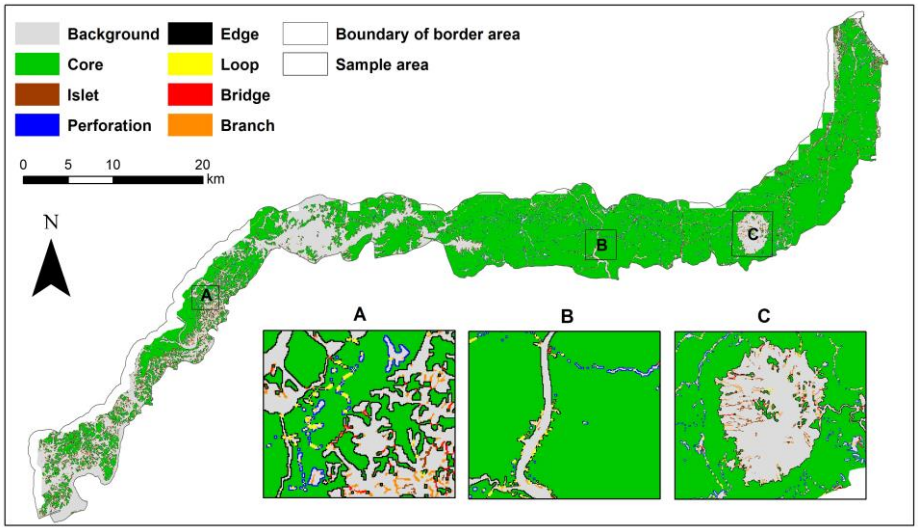


Figure 4. Distribution map of each morphological spatial pattern analysis (MSPA) class. Points (**A**–**C**) represent randomly selected areas with different forest landscape distribution characteristics.

Table 3. Characteristics of each MSPA class. The background area includes non-forested and non-investigated areas. The units of area and percentage are km^2 and %, respectively.

MSPA Class	Area (Percentage)				
	PJ	YC	CW	GW	Total
Background	131.69 (64.23)	172.77 (51.42)	159.98 (38.96)	119.78 (11.32)	584.23 (29.07)
Core	45.39 (22.14)	120.21 (35.78)	217.84 (53.05)	864.09 (81.66)	1247.54 (62.07)
Islet	0.45 (0.22)	0.80 (0.24)	0.30 (0.07)	0.85 (0.08)	2.40 (0.12)
Bridge	0.42 (0.20)	1.90 (0.57)	4.76 (1.16)	24.20 (2.29)	31.28 (1.56)
Edge	19.37 (9.44)	28.41 (8.46)	20.02 (4.88)	27.61 (2.61)	95.41 (4.75)
Loop	1.10 (0.54)	2.35 (0.70)	3.45 (0.84)	13.63 (1.29)	20.54 (1.02)
Perforation	2.90 (1.41)	3.74 (1.11)	1.67 (0.41)	4.10 (0.39)	12.41 (0.62)
Branch	3.72 (1.81)	5.81 (1.73)	2.59 (0.63)	3.85 (0.36)	15.97 (0.79)
Total	205.03 (100)	336.00 (100)	410.61 (100)	1058.13 (100)	2009.77 (100)

A total of 2058 core patches were identified in the study area, with a mean area per patch of 0.71 ± 8.93 km^2. The number of core areas distributed in each region was the greatest in YC (n = 692), followed by PJ (n = 519), GW (n = 437), and CW (n = 400), with the mean area as follows: GW (1.92 ± 16.91 km^2), CW (0.72 ± 7.30 km^2), YC (0.14 ± 1.18 km^2), and PJ (0.05 ± 0.19 km^2), indicating an increase in core area toward the east (Table 3).

The distribution of dPC estimated for the core patches in each region is presented in Figure 5a. Compared to the connectivity estimated for the entire study area (Figure 5b), the patches critical for protecting connectivity throughout the study area were distributed evenly in each region. An analysis of the entire study area revealed a trend of a concentrated distribution of most high-connectivity core patches toward the east, where there is a high forest density. The mean dPC of the core areas of the entire study area was 0.45, while the highest connectivity for the core patches was 78.42 ± 2.16 standard deviation. The CW region had the highest mean connectivity index (0.54 ± 4.41), followed by GW (0.49 ± 4.30), PJ (0.47 ± 1.89), and YC (0.34 ± 3.02) (Table 4).

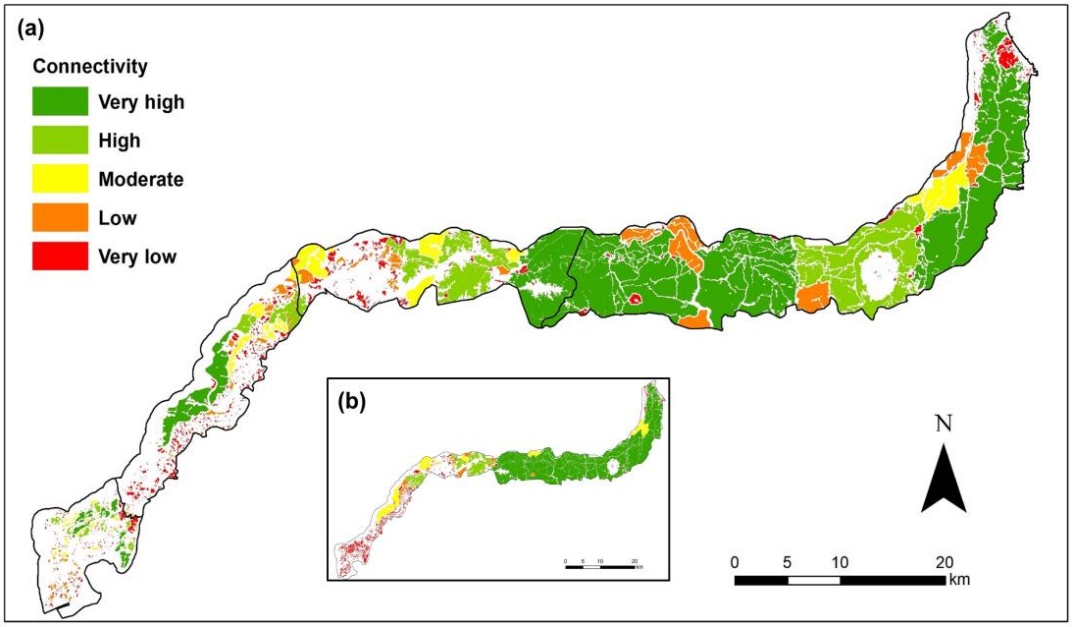


Figure 5. Comparison of a map that combines the connectivity indices (dPC) analyzed for (**a**) each region and a map that analyses connectivity for (**b**) the entire study area at once. (**a**) A regionally even distribution of high-connectivity forests across the study area, denoted by green areas. In contrast, the figure in (**b**) reveals that these high-connectivity forests are predominantly confined to the eastern regions, as indicated by the concentration of green.

Table 4. Description of patch area and connectivity for each region (Aver.: Average value, Max.: Maximum value, Std.: Standard deviation).

Region	Count	Area (km^2)			Connectivity (dPC)		
		Aver.	Max.	Std.	Aver.	Max.	Std.
PJ	529	0.05	2.04	0.19	0.47	18.91	1.89
YC	692	0.14	20.72	1.18	0.34	53.16	3.02
CW	400	0.72	140.12	7.30	0.54	78.42	4.41
GW	437	1.92	220.85	16.91	0.49	59.10	4.30
Total	2058	0.71	220.85	8.93	0.45	78.42	2.16

3.2. Clustering Area by Landscape Connectivity

The spatial autocorrelation analysis of forest landscape connectivity reveals a distinct distribution pattern of high–high (HH) and low–low (LL) connectivity clusters across the study area. In the PJ and YC regions, there is a notable gradient in landscape connectivity (Figure 6), with lower connectivity observed on the western side and higher connectivity on the eastern side. The CW region exhibits a contrasting pattern, with lower connectivity on the southern side and higher connectivity on the northern side. The GW region presents a more complex scenario where HH and LL clusters are interspersed, indicating a mixed-connectivity landscape.

3.3. Ecological Network and Proposed Protected Area

A comprehensive ecological network stretching 452.36 km was established, designed to interlink core ecological source points across various regions (Figure 7). This network meticulously weaves through the border area, creating vital ecological corridors for several endangered species native to these habitats. The network specifically supports species such as *H. suweonensis*, *G. japonensis* and *G. vipio* in the PJ region; it continues through the YC region sustaining populations of *G. japonensis* and *G. vipio*; it supports *M. moschiferus* in the

CW region; and it provides critical habitat connectivity for *U. thibetanus ussuricus* and *N. caudatus* in the GW region (Table 5).

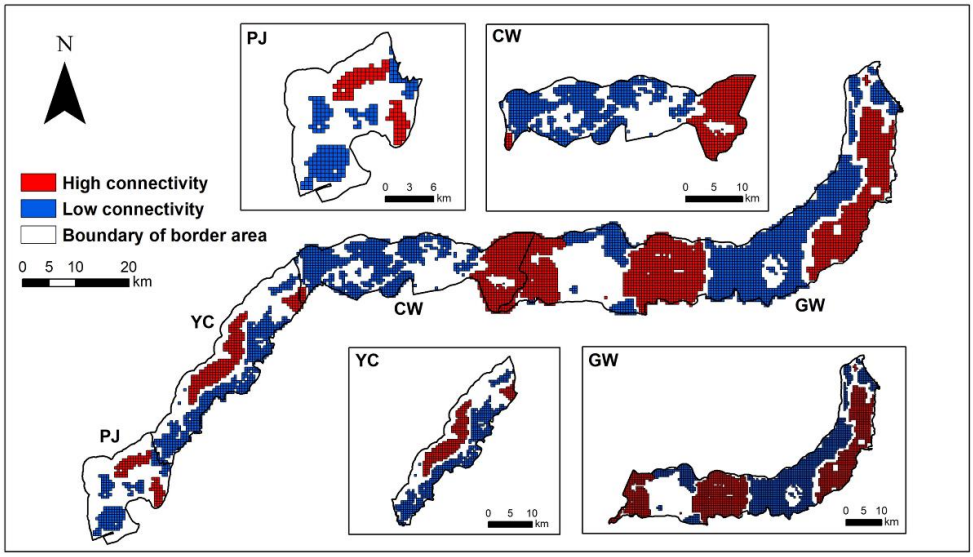


Figure 6. The local autocorrelation distribution of the connectivity index (dPC) for the core patches.

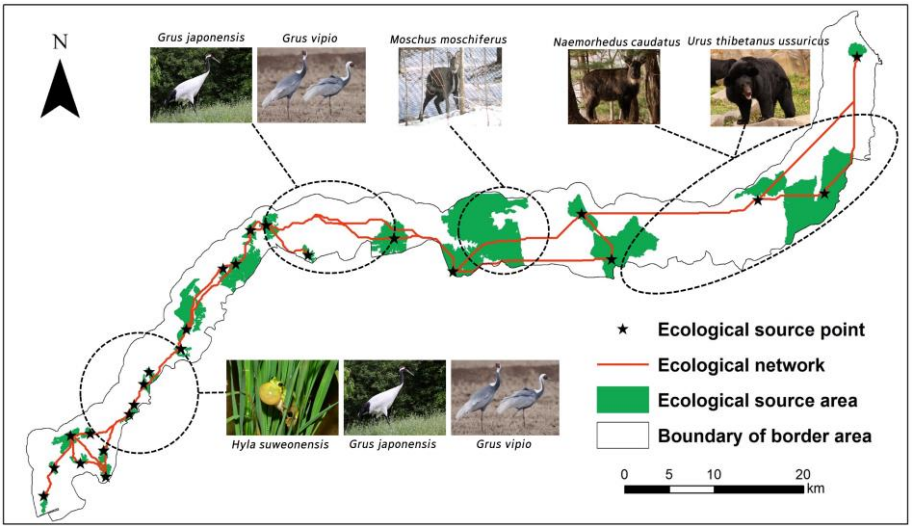


Figure 7. Paths comprising the ecological network developed based on forest landscape connectivity and distribution of the main endangered species. Photos of endangered species were obtained from the National Institute of Ecology (https://www.nie.re.kr/nieEng/main/main.do) (accessed on 23 September 2022).

Table 5. Classification and habitat characteristics of major endangered species in the study area. Appendix I lists species that are the most endangered among CITES-listed animals and plants, and Appendix II lists species that are not necessarily now threatened with extinction but that may become so unless trade is closely controlled.

Species Name (Scientific)	GDEW	IUCN	CITES	GDRL	Major Habitat Type	Major Behavior
Moschus moschiferus	Class I	VU	Appendix II	CR	Forest area, Mountainous region	Seasonal movement; Altitudinal migration
Hyla suweonensis	Class I	EN	-	EN	Wetland, Aquatic vegetation area	Breeding behavior; Egg laying on rice paddy

Table 5. *Cont.*

Species Name (Scientific)	GDEW	IUCN	CITES	GDRL	Major Habitat Type	Major Behavior
Grus japonensis	Class I	EN	Appendix I	EN	Wetland	Feeding behavior; Foraging in rice paddy and field
Grus vipio	Class II	VU	Appendix I	NT	Wetland	Feeding behavior;Foraging in rice paddy and field
Ursus thibetanus ussuricus	Class I	VU	Appendix I	EN	Forest area	Territoriality; Wide homeranges with seasonal variations
Naemorhedus caudatus	Class I	VU	Appendix I	VU	Forest area, Mounatinous terrain	Movement; Agile climbers, adapted for steep and rugged terrain

GDEW: Government-designated endangered wildlife, IUCN: IUCN Red List, GDRL: Government-designated Red List, CR: Critically endangered, EN: Endangered, VU: Vulnerable, NT: Near threatened.

The forests along the developed network are presented in Figure 8. The total area of these forests was 730.17 km^2, with the areas of protected forest covering 165.84 km^2. Based on this, forests not yet designated as protected areas (564.33 km^2) were selected as potential candidates.

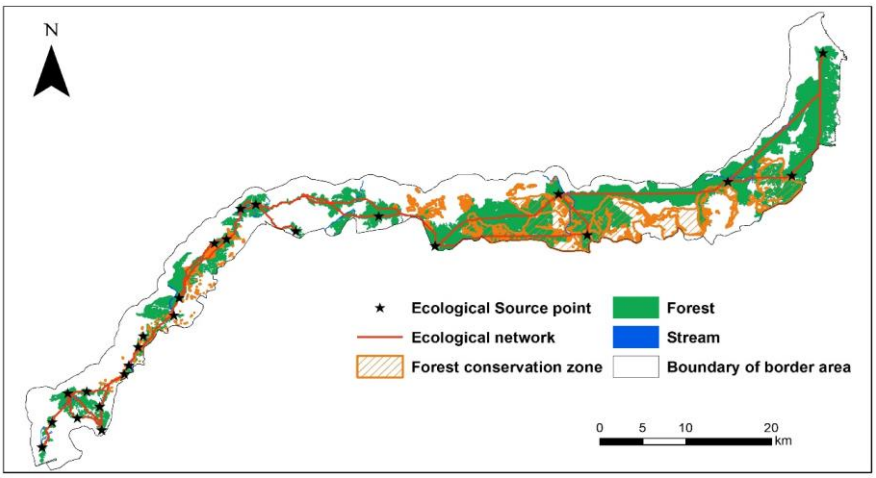


Figure 8. Forest conservation network in the study area. The map shows the established ecological network (red line) connecting forests (green) and currently designated forest conservation zone (orange), with key ecological source points (stars). Forests not currently designated as a forest conservation zone have been identified as candidates for additional protected areas.

3.4. Comparing the Results of Constructing an Ecological Network with Global Approach

In constructing an ecological network across the study area, the sectional (stepwise) approach (Figure 8) demonstrated superior efficacy over the global approach (Figure 9). The topography-driven forest distribution, with high connectivity forests in the east and low connectivity in the west, necessitated a tailored strategy. Our sectional method, considering regional land-use characteristics, yielded a more effective ecological network, enhancing connectivity where it is most needed. This approach's alignment with local spatial management ensures its practical applicability and potential for successful implementation in South Korea's forest conservation efforts.

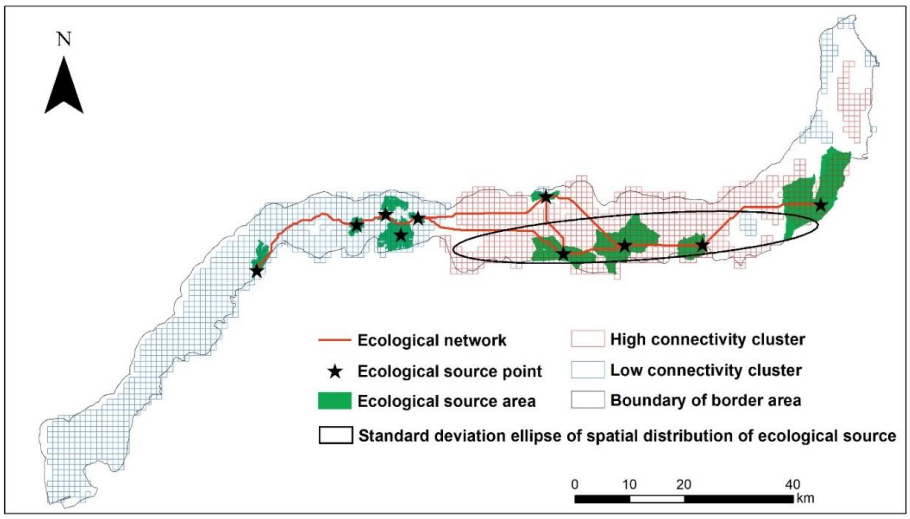


Figure 9. Ecological network produced through a global analysis of landscape connectivity. The black line indicates central tendency, dispersion, and directional trends of ecological connectivity based on the forest patch connectivity index (dPC) derived using the Directional Distribution tool of the ArcGIS 10.7 software.

4. Discussion

4.1. Constructing Effective Ecological Networks That Take into Account Terrain and Land Use Characteristics

The establishment of ecological networks plays a crucial role in facilitating the colonization of wide-ranging species, primarily through the enhancement of species mobility and genetic exchange. These networks also have broader ecological implications: they can reduce habitat fragmentation, augment biodiversity, support pollinator migration, and enable species to adapt to climate change [16–18]. When targeting a particular species, it becomes imperative to incorporate coefficients that accurately reflect its behavioral traits, including home range and seasonal movement patterns, to compute the least cost distance. Integrating these extensive ecological benefits significantly augments the methodology of the current study, rendering it highly effective for the development of species conservation strategies that improve habitat connectivity. However, in this study, due to the absence of specified target species and the focus on establishing ecological network pathways to enhance forest connectivity, coefficients from prior studies were adopted, especially pertinent in regions with significant land-use intensity gradients, as observed in the study area.

Owing to the topographic characteristics of the Korean peninsula, where the east presents a high altitude and steep slopes and the west a low altitude with milder slopes, most forests are found concentrated on the eastern side, while human land-use areas, such as developed and agricultural areas, tend to be concentrated in the west. Hence, in constructing a longitudinal forest landscape network, there is the potential for a broad approach to producing a network biased towards the forests in the east. Even within the eastern area, the forest patches with the highest connectivity were concentrated on the southern side, indicating that a global approach to constructing an ecological network would ultimately partially limit the scope to those concentrated areas. The approach is, thus, limited in enhancing the ecosystem quality throughout the forest landscapes by constructing an ecological network for the target area of spatial planning. The approach is, thus, limited in enhancing the ecosystem quality throughout the forest landscapes by constructing an ecological network for the target area of spatial planning. Informed by recent advancements in spatial planning [59,60], this study adopted a stepwise approach over the traditional global methodology [33–38], where paths of the ecological network were individually tailored for each region based on specific land use characteristics and topographical challenges of the Korean peninsula, culminating in a final network that connects these paths, proving more effective in achieving our conservation goals. Our eco-

logical network approach connected the forest landscapes more effectively than connections produced through a global approach. Because spatial management planning for natural environments in South Korea is conducted by each local government, the developed network is anticipated to prove effective in practice owing to its regional focus [61]. However, for an enhanced applicability of the method in policymaking, it is imperative that research on optimization persists to confront the inherent challenge associated with the stepwise methodology. This approach occasionally overlooks forests possessing substantial absolute connectivity but comparatively lower regional connectivity significance. This issue arises in the process of identifying core connectivity areas within highly connected regions. A case in point is the southwestern forests of the GW region, as depicted in Figure 6, which, despite their high connectivity, may be overlooked due to their relative positioning in the connectivity hierarchy. Addressing this limitation is crucial for refining the selection of key areas that contribute to overall ecological network efficacy.

4.2. Value of Ecological Networking in the South Korean Border Area

The ecological axis from the south to the north of the Korean peninsula, centered on a series of high-altitude mountain ranges on the eastern side, allows for relatively distinct compartmentalization, thus maintaining ecological connectivity to a certain degree due to limited land use by humans. However, connectivity is difficult to maintain along the ecological axis from the east to the west due to the land use by humans focused in the low-altitude regions. In this light, ecosystems at the border area with North Korea serve as a core axis of biodiversity in the Korean peninsula due to their limited land use by humans and uninterrupted connectivity due to the lack of roads, railroads, and urbanization [42]. However, as urban sprawl increases due to the overpopulation of metropolitan cities in South Korea, the pressure of human-related development is increasing, even near the border area [62]. In addition, the installation of structures for military purposes and road blockades used in the cold war landscape [63] could isolate forest ecosystems. The ecological connectivity-based management of border-area forest ecosystems is, thus, essential for conserving biodiversity in the Korean peninsula. Furthermore, considering regional characteristics with a high frequency of forest fires for military purposes, followed by the recovery of the forest landscape, the study area is anticipated to serve as a valuable reference model area for spatial planning, aiming to restore and manage forest landscapes in fire-prone regions in future [64]. Because the border area is still subject to military activity between South Korea and North Korea, the risk of remnants of war, such as landmines, limits the ability to thoroughly plan for managing forest ecosystems based on field surveys. To resolve such limitations, the current distribution of forests was determined by analyzing KOMPSAT-3 satellite images, aerial orthophotos, and the use of a national land-cover map [44] with classifications based on spatial thematic maps constructed by government agencies, such as the national forest and digital topographic maps. The paths of a forest ecological network that ensure landscape connectivity were drawn using the active and recently developed GIS-based spatial analysis. The methods applied in this study may prove effective in spatial planning for landscape ecosystem conservation in areas where field surveys are limited due to the large scale of the area or restricted access. It should also be noted that the structural integrity of forest patches determined in field surveys should be considered when deriving core forest patches to further enhance the effects of the constructed ecological network [65,66]. In addition, various ongoing studies are estimating the forest conservation value using remote sensing techniques [67–69], and the findings should be considered for constructing effective ecological networks, even in areas with a limited scope for field surveys.

4.3. Establishing Protected Areas for Ecological Connectivity in the South Korean Border Area

With the goal of forest ecosystem conservation, the South Korean government has designated legally protected areas for land management, including natural parks, ecological and scenery conservation areas, forest conservation zones, Baekdu-daegan protection areas,

and protection districts for wildlife [70]. The total protected area, excluding duplicated areas where there are multiple designated protected areas, is around 10,160 km^2 [9], accounting for approximately 10% of the total terrestrial area of South Korea (100,341.8 km^2 as of 2021) [71]. Except for the Baekdu-daegan protection areas along a series of mountain ranges on the eastern side of the Korean peninsula, most protected forest ecosystem areas are separated by independent mountains. Ultimately, such natural compartmentalization is effective for preventing habitat loss and fragmentation within each protected area, despite the possibility of isolation due to changes in land use outside the protected area [72], making it difficult for the benefits resulting from forest protection to spread to neighboring, possibly unprotected, forests. Notably, land use by humans, mainly in low-altitude regions, may limit natural ecological processes, such as the migration and dispersal of wildlife that inhabit adequately conserved forests [73], and designating protected areas without considering ecosystem connectivity will not lead to the enhanced quality of overall forest ecosystems in each region.

Furthermore, while the Baekdu-daegan protection areas may be considered useful for adequately managing the functional connectivity of forest ecosystems in the north and south, besides differences in climate due to latitude, these areas exhibit mostly similar topographic characteristics. Hence, the diversity of forest landscape connectivity cannot be guaranteed regarding the topographic characteristics on a macroscopic level on the Korean peninsula. On the contrary, to ensure the effective conservation of national forests, it is necessary to increase connectivity across various forest and water edge ecosystems that develop along the macroscopic topography gradient from the east to the west. However, this has not been considered when designating most protected areas in South Korea. Thus, an effective method for designating protected areas that can connect various forest landscape classes in the east-to-west direction is expected to be useful for promoting forest management. The Korean Ministry of Environment in South Korea has already constructed a GIS-based digital thematic map that presents the level of conservation of the national ecosystems, such as the ecological and natural maps and the urban ecological map. These maps could be used to select forests with high conservation values as protected areas. Conversely, it is difficult to ensure that protected forest ecosystem areas selected according to the conservation level will reflect ecosystem connectivity as the criterion for assessing the conservation level as indicated on the maps, especially when it comes to assessing the conservation of vegetation and the structural integrity of plant communities. The vegetation metrics consider plant distribution and rarity, plant nativity, presence or absence of potential natural vegetation, the vertical structural integrity of the plant community, the time required for the community to develop, and inhabitation by plant species critical to conservation ecology. Thus, alongside valuable data for defining the structural conservation value of forest ecosystems, ecological connectivity will be useful for designating protected areas to best reflect both ecosystem structure and function. In this respect, the findings of our study on developing a method to establish a forest ecological network for the South Korean border area are anticipated to contribute to spatial planning for designating and managing protected areas in South Korea in the future.

5. Conclusions

South Korea has a considerably high population density (25th on the global scale and 516/km^2 as of 2020) [71], with mountains constituting approximately 70% of the terrestrial land [74], and a land mass is characterized by differential land use characteristics to the east and west. The border area is the only terrestrial ecological axis in the east-to-west direction that has not been significantly impacted by rapid urbanization, making it a critical region for biodiversity conservation. It is necessary to develop conservation measures against potential forest landscape damage due to the increasing developmental pressure on this region. This study was conducted to establish an ecological network aiming to enhance forest landscape connectivity in the border area in South Korea, and the following conclusions were drawn.

(1) Considering the macroscopic topographic characteristics of the Korean peninsula, such as a high altitude in the east and a low altitude in the west, with consequently varied land use patterns, the study area was divided into four regions. We selected the core source forest patches for each region by analyzing the forest landscape connectivity in each region. The paths drawn for constructing an ecological network were connected to reflect all paths throughout the study area. This method allowed for more effective connections throughout the area than those derived from a global analysis; hence, our method is anticipated to enhance the ecological connectivity of the entire study area.

(2) A forest network spanning 452.36 km^2 to connect the core source forest patches in each region effectively connects the habitats of the main endangered wildlife species inhabiting the study area. The developed network is, thus, anticipated to serve as an ecological corridor. Furthermore, to enhance forest ecosystem connectivity in the border area, it is necessary to consider forests of 564.33 km^2 in the vicinity of the network paths as candidate forest conservation zones, which would contribute to achieving Target 3 outlined in the Post-2020 Global Diversity Framework.

(3) The method applied in this study will prove effective for constructing ecological networks of two areas with unique land use and topographic characteristics while remaining versatile owing to its simple, intuitive, and quantitative analytical process.

(4) Because this study utilized limited spatial information, only ecological functions were considered in the selection of forest reserve sites. However, it is believed that a more effective selection of reserve sites can be achieved by considering spatial information that considers the structural value of forest patches. In addition, although this study focused on establishing a method for optimal network construction, it is necessary to calculate the optimal resistance value according to the regional characteristics and the purpose of network construction when utilized for designing policy.

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