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Conserving terrestrial linkages that connect natural landscapes of the Korean Peninsula

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Abstract Human-induced land degradation fragments natural ecosystems, hinders ecological processes, and threatens biodiversity. Maintaining or restoring ecological flows across landscapes through landscape linkages may provide a solution. Here, we identify a peninsula-wide ecological connectivity network for the Korean Peninsula using two linkage mapping models. We found three major north-south axes of connectivity traversing the Demilitarized Zone (DMZ), which emerged as an important east-west linkage. Only 7% of the highest-ranked connections are currently secured by protected areas. We found 120 linkages in North and South Korea that are intersected by road networks consisting of motorways and trunk roads under both models. These locations should be the focus of immediate attention for conservation planners, as well as 274 and 1130 additional road-impacted linkages under one model or the other. The results can be used for policy support, and potentially as a basis for the two countries to engage in discussions about ecosystem health and climate change adaptation. The approach presented here can also be efficiently used to assess and map natural landscape linkages.

Keywords Corridors · Graph theory · Landscape connectivity · Landscape fragmentation · Landscape permeability · The Korean Demilitarized Zone

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Introduction

Human activities are among the most significant factors behind land transformation and fragmentation of natural vegetation (Vitousek et al. 1997; Foley et al. 2005; Sanderson et al. 2002). The loss and damage to natural vegetation from fragmentation affects ecological connectivity (Fahrig 2003; Crooks and Sanjayan 2006). The consequences are pernicious and involve changes in species composition and diversity, as well as changes in ecosystem processes and patterns (Saunders et al. 1991; Vitousek et al. 1997; Fahrig 2003).

Several studies highlight the importance of multiple-scale approaches to landscape fragmentation assessment. They document the need for informed planning of conservation programs, such as corridors (here referred to as linkages) and the spatial configuration of remaining resource patches in both the scientific and political arenas (Marulli and Mallarach 2005; Stephens et al. 2004; Harrison and Bruna 1999). This network of corridors and habitat patches is often called landscape connectivity, a term that can include both structural connectivity (the physical arrangements of patches) and functional connectivity (the movement of individuals between patches) (Brooks 2003; Baguette et al. 2013). Methods for modeling landscape connectivity generally fall into those that model the spatial needs of focal species (Choe et al. 2017) and those that use the physical attributes of the landscape structure to identify avenues of connectivity (Keeley et al. 2018). While focal species-based approaches can be useful for conservation planning of individual species (e.g., Carroll et al. 2012), or regional conservation designs that use umbrella species (Thorne et al. 2006), the actual structure of a landscape has been advanced as a way to grapple with landscapes more generally (e.g., McRae et al. 2008). Landscape structure can be argued to represent functional connectivity (Gonzalez et al. 2008). Using structural connectivity provides a number of advantages including availability of remote sensing data to identify patterns of vegetation and other GIS data. It can be considered the first level of connectivity modeling used when more detailed species data is not available or is insufficient to permit targeted modeling (Keeley et al. 2018).

We applied a structural analysis of connectivity using two models to the Korean Peninsula and asked where landscape-scale connectivity is found. Here, we considered connectivity to be a function of a continuous gradient of permeability values based on a landscape's "naturalness" (i.e., degree of human disturbance) (McGarigal et al. 2009; Carroll et al. 2012; Theobald et al. 2012) rather than attempting to identify discrete patches based on subjective thresholds of habitat area, quality, or neighborhood distance. By calculating the gradient of landscape permeability combined with network centrality measures, we assessed connections among all potential patches, not just user-defined locations, within the entire analysis extent, resulting in a hexagonal lattice network with the connections represented as nodes. We then tested the resulting connectivity network in two ways. First, we examined how much of the connectivity network is already protected. Second, we identified where the network was crossed by major roads. Roads are well-known to be sources of mortality for various types of wildlife (Forman et al. 2003), and in Korea, they have been shown to impact birds, mammals, reptiles, and especially amphibians (Seo et al. 2015). Thus, we used road intersections as an index of risk for wildlife.

As elsewhere, the Korean Peninsula has experienced the consequences of landscape fragmentation and climate change impacts (Kang et al. 2016a). Although the Republic of Korea (hereafter, South Korea), with current forest cover accounting for approximately 64% of its total land area, is regarded as a success in forest restoration (begun in the early 1970s through the government-led reforestation policy) (Bae et al. 2012), population growth and increased economic development in the last few decades have led to substantial changes in land use and land cover, including a 16% decrease in farmland, a 55% increase in residential land use, and a 96% increase in road cover (Park et al. 2011; Statistics Korea 2017). In addition, the Democratic People's Republic of Korea (hereafter, North Korea) has also undergone both deforestation and fragmentation since the 1980s (Kang and Choi 2014). However, there is limited information on the effects of this fragmentation on regional ecosystems and landscape connectivity across the entire Korean Peninsula.

The two Koreas are ecologically and biogeographically connected. However, most landscape studies have focused on either South Korea or North Korea (e.g., Choe et al. 2017; Kang and Choi 2014). Therefore, in this study, we aim to identify and assess the following: (1) the structural landscape networks of the entire Korean Peninsula using the graph- and circuit-theoretic connectivity models; (2) the effectiveness of existing protected areas in the context of regional landscape connectivity; and (3) linkage routes with additional potential threats to maintaining connectivity due to road networks. Through this research, we hope to contribute to the understanding of terrestrial ecosystem connectivity on the Korean Peninsula and provide a scientific basis for connectivity conservation programs in both countries.

Materials and methods

Study area

The Korean Peninsula (excluding its islands) lies between latitudes 34° and 43° N and longitudes 124° and 130° E and covers ca. 219,672 km^2 (Fig. 1a). South Korea occupies approximately 45% of the total

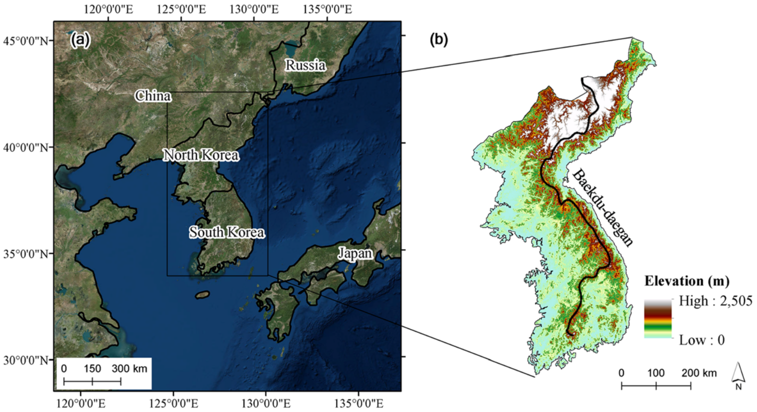

Fig. 1 Geographical location and elevation of the Korean Peninsula. Panel **a** shows an aerial photograph of the Korean Peninsula as a part of Northeast Asia (ESRI 2019). Panel **b** shows a digital elevation model of the Korean Peninsula. The ridgeline of main mountain range of the Korean Peninsula (i.e., the Baekdu-daegan) is also marked

land area and North Korea the rest. The Peninsula has an average elevation of roughly 450 m above mean sea level and about 70% of the land area is mountainous, located mostly in the north and east (Fig. 1b).

The climate varies with location: southern areas experience typically warm and wet weather due to the East Korean Warm Current, whereas northern areas are relatively cold and dry. The climate and topography of the Peninsula influence biodiversity and species distribution. The area is often categorized into warm-temperate, temperate, and cold-temperate zones, with most of the Peninsula located within the temperate zone. About 100,000 indigenous species have been recorded on the Peninsula (ME 2014).

Methods

A three-step process was used to identify terrestrial landscape linkages and assess their connectivity: (1) we created a landscape permeability map to reflect natural vegetation. We assumed higher quality or values would be more suitable for dispersing species; (2) we modeled a second landscape connectivity map using the shortest path and current flow techniques and mapped critical and important linkage areas; and (3) we examined the resulting networks from the first two outputs to quantify the conservation performance of existing protected areas (hereafter, PAs) for connectivity and to examine the level of risk to key linkage routes from major road crossings.

Creating the landscape permeability surface

The landscape permeability surface was constructed based on a classification of vegetation quality and naturalness, which was then used to determine connectivity and dispersal routes, which represent how a landscape facilitates or impedes movement (Taylor et al. 1993). Referring to the method applied by Pinto and Keitt (2009), we used three land use/land cover maps to estimate the degrees of landscape permeability to natural ecological flows and movements. First, the MODIS vegetation continuous fields (MOD44B) data for the year 2009 was employed, which contained estimates of percentage tree cover at 250-m spatial resolution (DiMiceli et al. 2011). Second, we used a human footprint map at 1-km spatial resolution (Sanderson et al. 2002), which contained estimates of human impact ranging from 0 (undisturbed) to 100 (most disturbed). These estimates were based on population density, land transformation, access, and electrical power infrastructure. The original values were inverted to generate a grid with values ranging between 0 (most disturbed) and 100 (undisturbed). Third, we used the 300-m GlobCover 2009 land cover map (Bontemps et al. 2011) as the underlying base map and the 500-m MODIS-based global land cover climatology (Broxton et al. 2014) as the second map, which included information on the distribution of vegetation types (e.g., forest, grassland, agricultural land) and other land covers (e.g., urban areas, bare areas, water bodies). These were merged into a 500-m land cover map, containing eight coarser classes (forest, shrubland, grassland, wetland, agriculture, barren land, developed, and water), which yielded an accuracy of about 80% when compared with aerial imagery of the study area. We assigned each land cover class the following relative permeability values (ranging between 1 and 100): forest and wetland (100); shrubland (50); grassland (30); water and barren area (20); agricultural land (10); built-up area (1), based on values from the literature (Theobald et al. 2011; Teng et al. 2011; Spencer et al. 2010) and the land cover map of the study area. Since natural resource managers in both South and North Korea, where their lands are predominantly covered by mountains (ca. 70%), are pursuing large-scale terrestrial restoration to ensure the conservation and sustainable use of forest and wetland ecosystems and their services (Lee and Miller-Rushing 2014), we assume this ranking to roughly correspond to the habitat requirements of most vertebrate species from the Peninsula. To obtain the final integrated map of landscape permeability, we rescaled the other two raster maps to a 500-m grid resolution and then averaged the three raster maps. The permeability surface was extended 25 km into peripheral areas to avoid bias that could be caused by choosing a study area as per merely administrative boundaries (i.e., the China–North Korea and North Korea–Russia borders).

Landscape graph modeling

We employed a graph-theoretic approach for quantifying landscape connectivity (Carroll et al. 2012; Crooks and Sanjayan 2006; Urban et al. 2009). Graph theory has been applied as an efficient, robust tool in various ecological fields such as landscape ecology and conservation planning (Urban et al. 2009). In a graph model, a landscape can be represented as a set of nodes (e.g., resource patches) connected by inter-node links (e.g., via dispersal or movement of organisms) with a binary patch-matrix structure framework (Urban et al. 2009; Galpern et al. 2011). Rather than attempting to delineate discrete patches based on subjective thresholds of patch size or quality, alternative non-patch-based graph models have been proposed (e.g., Carroll et al. 2012; Theobald et al. 2012). In this study, we utilized a landscape lattice approach (Carroll et al. 2012) for representing complex landscape patterns as regular lattices based on a gradient of permeability, which enabled more sophisticated graph analyses with network-based ranking methods, i.e., centrality metrics.

We applied two landscape connectivity-mapping methods (shortest path and current flow betweenness centrality; here termed “shortest path” and “current flow,” respectively) to the landscape permeability surface derived in step 1 and measured the role of nodes in mediating ecological flows between all possible pairs of nodes within a hexagonal lattice-based graph. Shortest path identifies one or several least-cost (shortest) paths between each pair of nodes in a graph and counts the number of least-cost paths that pass through each node (Borgatti and Everett 2006). Conversely, by modeling random walk paths based on circuit theory (McRae et al. 2008), current flow identifies multiple pathways between each pair of nodes and counts how often a node is passed through by a random walk between two other nodes (Newman 2005). As such, these two methods are distinct in terms of movement characterization and also complement one another (Marrotte and Bowman 2017).

We divided the region into a lattice composed of hexagons, each with an area of 50 ha (0.5 km^2). The centroid of each hexagon became a node (total 442,511 nodes), which was connected to its six neighboring hexagons. The landscape lattice resolution (i.e., 50 ha) was chosen to ensure computational feasibility. As an undirected graph, edge weights were obtained from the mean permeability value of the edge’s two end nodes. Graph analyses and connectivity metrics were computed using the Connectivity Analysis Toolkit (Carroll et al. 2012).

Linkage identification and connectivity assessment

Shortest path generally follows a positively skewed distribution whereas current flow follows an un-even (or even) distribution, rather than a normal distribution (Carroll et al. 2012). Spatially, current flow identifies linkage areas encompassing the linkages derived from the shortest path, but these areas are more diffusely distributed than are the shortest-path priority areas (Carroll et al. 2012). Thus, given these distribution characteristics, for linkage mapping, we identified high priority linkage areas as hexagons with the top 1–5% and the top 1–20% of connectivity values for shortest path and current flow, respectively.

As one of three major geographic features in Korea (i.e., the central Baekdu-daegan mountain range, Demilitarized Zone (termed “DMZ”), and coastal and islands areas), the DMZ is 4 km wide for buffer zone stretching about 240 km across the Peninsula. This is not only well-known, effectively an untouched sanctuary for biodiversity (ME 2014) but, more importantly, according to its geographical location, might also be a veiled natural corridor, connecting natural areas of South and North Korea. For this reason, we examined main flow routes crossing the DMZ to present the most untouched natural linkage zones important for maintaining north-south regional connectivity.

Post-modeling linkage network assessment

We also explored whether highly connected locations are protected within the PAs of the Korean Peninsula. The World Database on Protected Areas (WDPA) for November 2017 provided the vector data of PAs with a "designated" status (IUCN and UNEP-WCMC 2017). For PAs of North Korea included in the WDPA only as points with unknown boundaries, a circular buffer around the point with an area equal to the listed area was created and used in the analysis.

Finally, we identified key landscape connectivity routes with additional potential threats to connectivity due to road networks. To do this, we computed the spatial intersection of the shortest path and current flow maps with major roads. The OpenStreetMap database for November 2017 provided road network vector data, including the following four major road types: motorways, trunks, primary roads, and secondary roads (OpenStreetMap contributors 2015). All spatial maps were created using ArcGIS 10.1 (ESRI 2012).

Results

Figure 2 shows the naturalness-based quality, or permeability, of heterogeneous landscapes on the Korean Peninsula that we used to model landscape connectivity. Based on this map, the overall landscape linkages of the Peninsula according to the shortest path and current flow models can be quantified (Fig. 3).

The shortest path identified three main flow routes belonging to the top 1% that completely run through the east-to-west Demilitarized Zone (DMZ) (Fig. 3). The shortest path also identified a set of regionally critical paths (includes the top 1 and 5%), crossing longitudinal mountain ranges, e.g., from Mt. Baekdu in the north to Mt. Jiri in the south, which reflect high amounts of accumulated flow throughout the Korean Peninsula.

The top 20% of current flows are widely and continuously distributed in landscapes of the central regions of the Peninsula but are fragmented by cities, such as Seoul, Pyongyang, and their surrounding areas (Fig. 3). The top 1% most critical areas identified by the current flow comprise 2213 km^2. These locations are concentrated in parts of the adjacent four provinces of North Korea—Kangwon (59%, 1313 km^2), South Hamgyong (25%, 563 km^2), South Pyongan (8%, 180 km^2), and North Hwanghae (6%, 125 km^2). Areas with high current flow belonging to the top 20% cover largely the DMZ area (74%, 1648 km^2) (Fig. 3).

In the central regions of the Peninsula, linkage areas belonging to the top 20% of current flow encompass most of critical paths derived from the shortest path, including alternative paths surrounding the critical ones (Fig. 3). Across the Peninsula, areas belonging to the top 20% of current flow cover more than half (62%, 1382 km^2) of critical paths that belong to the top 1%

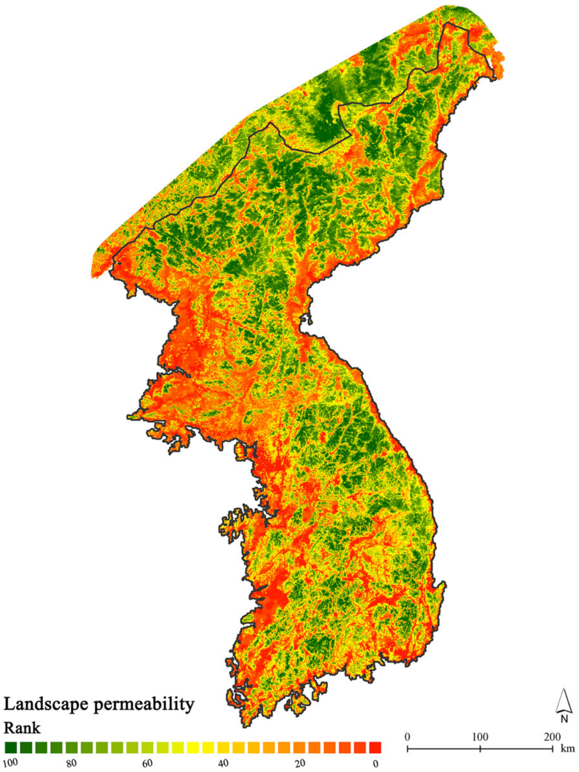

Fig. 2 Landscape permeability of land areas on the Korean Peninsula and surrounding areas. This map shows the distribution of permeability across the land surface based on a classification of vegetation quality and naturalness. The permeability value of each pixel is represented as a percentile rank

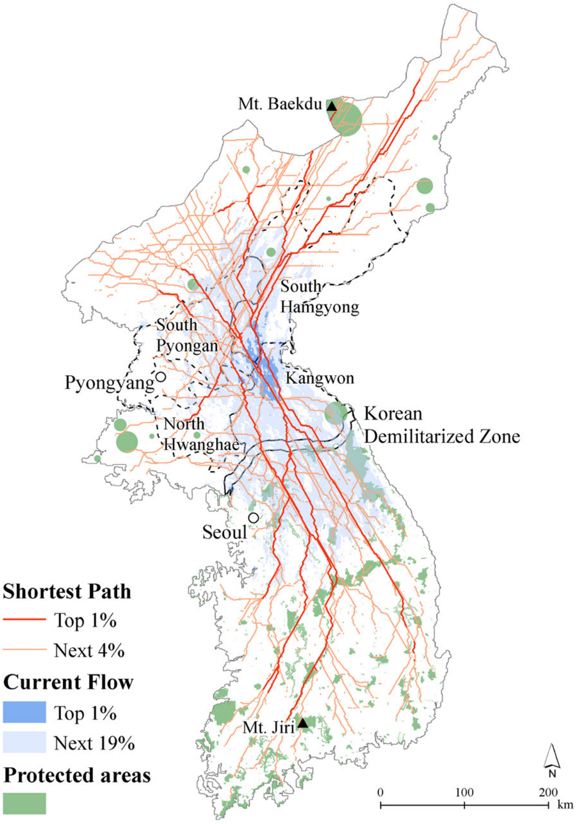

Fig. 3 Top-level linkages and protected areas of the Korean Peninsula. The high priority linkages connecting natural lands are identified according to the shortest path and current flow models

of shortest path and include 42,870 km^2 of other least-cost and alternative ones. These areas of high current flow also cover nearly half (43%, 4839 km^2) of high priority paths that belong to the top 5% of shortest path.

Most PAs do not appear to be in areas with a high flow accumulation, while regionally important routes traverse some PAs (Fig. 3). For both metrics, only 7% of high priority linkage areas (i.e., the top 5% and 20% of shortest path and current flow, respectively) are located within PAs. The central regions of the Korean Peninsula were identified as major gaps in existing protected area coverage. Specifically, in parts of the abovementioned four provinces of North Korea, the top 1% most critical areas important for regional connectivity were found to be completely unprotected.

We identified natural connectivity routes (i.e., key linkage routes) that intersect major roads and found a total of 2132 intersections between major roads and high shortest path (i.e., the top 5%) (Fig. 4). Specifically, the high connectivity routes of shortest path cross 208 motorways, 186 trunks, 825 primary roads, and 913 secondary roads. For current flow, we found a total of 8765 intersections between major roads and high connectivity areas (i.e., the top 20%) (Fig. 5). Specifically, the areas with high current flow cross 620 motorways, 630 trunks, 3394 primary roads, and 4121 secondary roads. We found that linkage routes with high shortest path intersect 394 motorways and trunk roads and high current flow 1250 with 120 overlapping locations showing both high shortest path and current flow.

Discussion

Our results provide the first comprehensive, spatially explicit landscape connectivity map of the Korean Peninsula. We found several north-south linkages that transect the Peninsula and identified significant connectivity functions of the DMZ. The results can contribute to prioritizing connectivity restoration and conservation planning for areas fragmented by urbanization or roads and potentially can be used as contextual information for climate change adaptation planning.

Both the shortest path and the current flow models identify the importance of connectivity of the Korea's central mountain range system, known as the Baekdudaegan mountains (Choi 2004). The shortest path model identifies several major north-south connectivity axes passing through these mountains (Fig. 3). The current flow model identifies important connectivity zones, including alternative paths surrounding the critical shortest paths (Fig. 3).

Several studies highlight the significance of the mountain range for its spiritual, sociocultural, and ecological aspects (e.g., Choi 2004; Kim and Cho 2005; Rho et al. 2005). However, in order to understand the ecosystem functions and processes of the mountain range and thereby develop conservation strategies, it will be essential to further research its ecosystem dynamics and integrate the importance of those ranges to regional connectivity. Our results, in this regard, reflect the network perspective, which is a critical part of ecosystem functioning, constituting ecological complexity. For example, the primary eastern north-south linkage area we identified (Fig. 3) was also recently identified as a potential climate change meta-corridor, being a potential northwards pathway

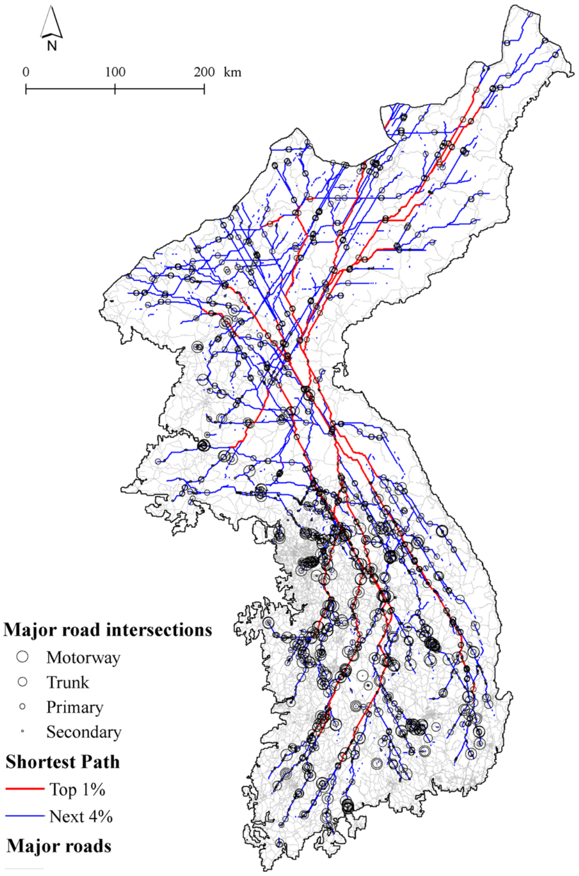

Fig. 4 Intersections of natural connectivity routes based on shortest path with major roads on the Korean Peninsula. Circles represent the locations of major roads with high accumulated natural flows and circle sizes indicate road levels

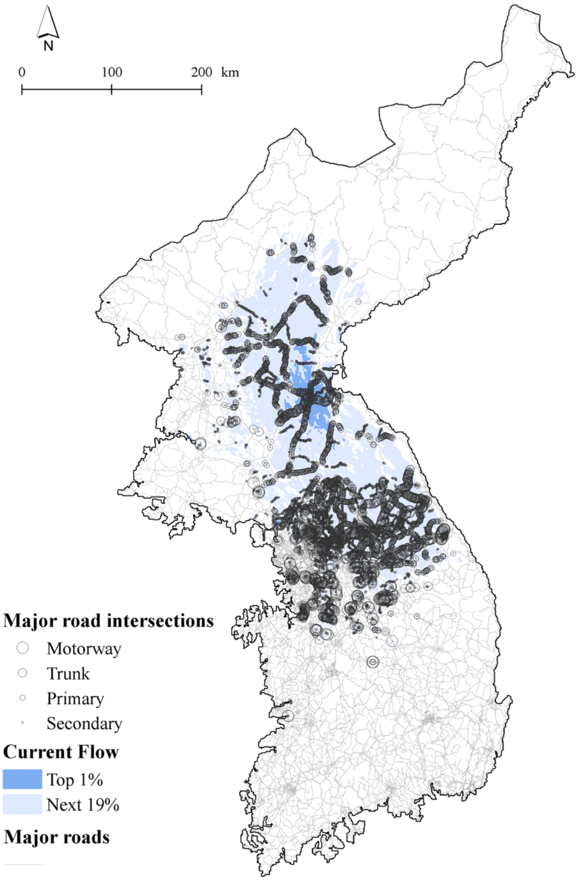

Fig. 5 Intersections of areas of high current flow with major roads on the Korean Peninsula. Circles represent the locations of major roads with high accumulated natural flows and circle sizes indicate road levels

accessible to a group of 157 climate-vulnerable plant species found in South Korea's eastern coastal mountains (Choe et al. 2017).

As the three major connectivity axes traverse the DMZ, both Koreas need to jointly focus on conservation priorities. This also indicates that robust conservation schemes for the DMZ should be based on research using both local and regional perspectives. The DMZ has been untouched for 60 years and thus is recognized as a significant reservoir of biodiversity, mainly in terms of local- or landscape-level patterns of species diversity. In addition to the intrinsic landscape and biodiversity value of the DMZ, national and local governments need to pay more attention to its vital role in maintaining relevant regional ecological flows.

We found little overlap between the PA network and the critical linkages, particularly for parts of the adjacent four provinces of North Korea—Kangwon, South Hamgyong, South Pyongan, and North Hwanghae (Fig. 3). These gaps may require the expansion of existing PAs and strategic establishment of new ones to maintain or improve landscape connectivity. As such, our connectivity network can help to identify specific areas where management and conservation policies should be reviewed and updated and where future development should be strictly limited or to anticipate the need for mitigation measures of adverse effects (Theobald et al. 2012).

Previous studies have highlighted the importance of the quantitatively assessing the number of intersections between transportation and ecosystem networks, to quantify which areas are most likely affected by the human development activities (Theobald et al. 2012; Kang et al. 2016b; Girardet et al. 2015). Road size and traffic volume are also important variables in determining risk to wildlife

(Forman and Alexander 1998). The data on North Korea's traffic volume are rare, whereas most of our prioritized landscape linkage-road intersections in South Korea have a large volume of traffic (roughly 9000 vehicles per day according to annual average daily traffic data provided by the Traffic Monitoring System (http://www.road.re.kr)). Our findings of the many intersections of natural connectivity routes with major roads can be used to identify where road-crossing structures may be needed to restore connectivity and reduce the high risk of wildlife roadkill, such as leopard cats (*Prionailurus bengalensis*) and oriental scops owls (*Otus sunia*) with wide distribution ranges (Seo et al. 2015). As a next research step, the validation of our modeled high-risk intersections with empirical data and monitoring would be useful to inform connectivity conservation implementation. Furthermore, assuming that there are a number of ecosystem fragments remaining in urban areas, which are important despite limited size, attention should be also given to fragmented areas in developed areas.

To offer complementary information for regional conservation planning, we used two contrasting linkage-mapping methods, shortest path and current flow. Many studies on ecological networks tend to focus on the shortest path method (Moilanen 2011). However, using only shortest path–based metric may underestimate other important components of ecological networks that are in the close vicinity of shortest paths but do not overlap with them (McRae et al. 2008). These areas can also increase the availability of alternative multiple pathways (i.e., redundancy) for ecological processes, which would allow greater flexibility and diversification in conservation planning. In addition, it would be informative to evaluate complementary linkage areas, because there are areas where securing linkages is difficult to implement and alternative corridors may be an option. Given that most graph-theoretic methods are simplified representations of the complex interaction between landscape structure and animal dispersal behavior, a more rational approach may use contrasting metrics as complementary and alternative sources of information for conservation planning, rather than focusing on a single best one (Carroll et al. 2012).

Our study was designed to identify landscape permeability patterns and key linkage areas within the ecological network. By taking a network-based approach including the whole Peninsula, our research provides insight into connectivity planning to address environmental and ecological issues derived from not only urbanization and other human development activities such as road construction but also potentially for climate change. Our findings of the importance of the Baekdu-daegan mountain range provide context for conservation planning in and between the two Koreas and can be used to inform discussions about forestry and open space management, urban development, and transportation policies.

Overall, a network-based approach for landscape conservation at broad scales is essential to protect biodiversity from human impacts and climate change (Carroll et al. 2018). Enhancing ecological connectivity, mainly in relation to climate-related range shifts, has already been proposed as a strategy to minimize the negative effects of climate change (Heller and Zavaleta 2009; Krosby et al. 2010). Evidence suggests that global climate change is a major threat to species extinction at both local and global scales (Parmesan 2006; McCarty 2001). In particular, climate change presents a challenge for biodiversity conservation. Recent studies emphasize the need for landscape connectivity to allow for potential response time that species may need to adjust to new perturbations such as climate change (Fahrig 2003; Krauss et al. 2010; Zuidema et al. 1996; Keeley et al. 2018). As species' ranges shift, the landscapes outside of PAs may become inhospitable, even while PAs themselves may become less suitable (Heller and Zavaleta 2009). Thus, there is a need for increased focus on landscape-scale connectivity, in order to incorporate potential range shifts regardless of an area's protected or unprotected status (Heller and Zavaleta 2009; Fahrig 2003; Opdam and Wascher 2004). All of these point to the importance of network-based approach to the entire Baekdu-daegan mountain range and its branches, which cover extensive areas, for building ecological resilience of the Korean Peninsula (Choe et al. 2017).

Although climate change will increasingly create the need to complement and expand existing PAs and designate new PAs, political conflicts between two Koreas make it more difficult to implement regulations and assign conservation programs at sub-regional and landscape levels with an integrated endeavor. Nevertheless, the network-based approach entails an important lesson regarding fundamental characteristics of ecosystems, i.e., their processes and functions, which in turn provide humans with diverse ecosystem services and are perpetuated and controlled by self-regulating ecological network (Barabás et al. 2017). We hope our study provides ecological incentive for dialog between the two Koreas for the sake of the sustainability of both ecosystems and human societies on the Peninsula.

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