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Review

History and Future Challenges of Roadkill Research in South Korea

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Abstract: Roadkill has been one of the most problematic issues with wildlife under urbanization. South Korea, one of the fastest industrializing countries in the world, has been affected by the same roadkill issues and has researched how to mitigate wildlife–vehicle collisions (WVCs). In the present study, we aimed to (i) review scientific studies concerning roadkill conducted in South Korea (51 domestic, 15 international papers, 19 reports, and 1 thesis), (ii) compare bibliographic networks between international and South Korean roadkill studies, and (iii) discuss future challenges. From a search in the core collection of Web of Science peer-reviewed papers published from 1992 to 2022, keywords were extracted to create a bibliometric visualization map, using VOSviewer. Among the 85 articles related to WVCs, those about eco-corridors have steadily increased since 1998, while mitigation system and roadkill articles have been published since the mid-2000s. With increased awareness, more systems have been established, and research related to WVCs has been increasingly established. Currently, there are two systematic roadkill monitoring systems in South Korea, and an increasing number of modeling studies have suggested where roadkill hotspots are located. How to mitigate roadkill incidents has also been explored. A comparison of associations between international and Korean research shows that the network structures of Korean society were more disconnected and less dispersed. In addition, the keywords were narrower than those used in studies from the international community. Although studies on landscape connectivity and road ecology are few, their number and scope in South Korea have increased and broadened. These studies could be more rapidly developed in the future as some systems are equipped.

Keywords: wildlife–vehicle collisions; roadkill; bibliographic networking; South Korea

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1. Introduction

As wildlife–vehicle collisions (WVCs) have been one of the most problematic issues in the coexistence of wildlife and urbanization, related research has been conducted to alleviate these problems. The research topics include spatiotemporal hotspot definitions using species distribution models [1,2], and evaluation of the efficiency of mitigation methods, such as: fences [3,4], alert systems for wildlife [5], passage construction [6], and monitoring by citizens [7]. Research on conflict mitigation is increasingly relevant.

Worldwide, national policies have been established to mitigate WVCs [8,9]. Because connections between green areas have been considered an important issue in landscape ecology, the history of investigations into connectivity goes back more than 150 years [10]. Although road ecology has been investigated since the 1920s in Canada, the USA, and

Scandinavia, the discipline has only been of interest and investigated since the late 1990s in South Korea [8,10]. Although the Korean record is shorter than in other countries, mitigation policy there has been rapidly established as annual road density has increased. For example, South Korea now has 536 eco-corridors, which constitutes one of the highest densities in the world [11]. Thus, exploring the progress of Korean research on WVCs can provide a good example for researchers and policymakers who are engaged in transportation.

South Korea, one of the fastest industrializing countries in the world, has suffered the same WVCs issues [12]. A total of 36,863 cases were reported from 2004 to 2019 on 36 highways [13]. Another study estimated that more than 60,000 water deer (*Hydropotes inermis argyropus*), a common species, are killed by cars every year [14]. Since mitigation policies such as the construction of eco-corridors and fences in expressways have been broadly established, the number of roadkill incidents has decreased [13,15]. As studies connect science and policies, mitigation systems can be improved to reduce roadkill [4].

Several reviews have been published on roadkill research conducted in South Korea. Choe et al. [16] reviewed past research trends on roadkill but criticized the fact that most of the studies reviewed international articles to suggest policies, and Andersen and Jang [12] reviewed the impact and mitigation on the transportation infrastructure. However, these reviews lack a focus on the history of research related to WVC mitigation policies. In the present study, we aimed to (*i*) review roadkill scientific studies conducted in South Korea, (*ii*) compare bibliographic networks between international and South Korean roadkill studies, and (*iii*) discuss future challenges.

2. Materials and Methods

2.1. Situation of Road Construction in South Korea

South Korea has a land area of 100,210 km^2 and lies between 33 and 43° N, and 124 and 131° E. The countryside is mostly mountainous (approximately 64% of the national land area), particularly on the eastern side of the country (Figure 1). The length of roads in South Korea has increased continually, reaching 111,314 km in 2019 [13]. Road density for highway, national, and local roads in South Korea is a little higher than in the USA (1.05 vs. 0.68 km/km^2). Road length per vehicle (5.88 km/1000 vehicles) is much lower than in the USA (26.45 km/1000 vehicles), and Japan (15.85 km/1000 vehicles [17]). In 1994, the first eco-corridor was built along Bulgok Mountain, located in Bundang, Seongnam city [16]. Currently, 536 eco-corridors are in operation (https://www.nie-ecobank.kr (accessed on 21 November 2022)).

2.2. Review of Research Projects and Papers on Roadkill in South Korea

We reviewed literature that is significant for the research fields conducted in South Korea. This was retrieved from the core databases of the National Science and Technology Information Service (https://www.ntis.go.kr (accessed on 21 November 2022)), National Institute of Ecology (NIE, https://www.nie.re.kr (accessed on 21 November 2022)), Korea National Park (https://www.knps.or.kr (accessed on 21 November 2022)), National Institute of Biological Resources (https://www.nibr.re.kr (accessed on 21 November 2022)), and Korea Expressway Corporation (https://www.ex.co.kr (accessed on 21 November 2022)). The projects and articles (51 domestic, 15 international papers, 19 reports, and 1 thesis) considered for the review were identified by searching with the terms: "roadkill", "road-kill", "eco-corridor", or "connectivity of ecological axis". The search was performed on November 1, 2022, and the span was from 1999 to 2022. As the aims and topics of some research projects were considered to be similar, we did not include research to establish the breadth and trends of the topics related to WVCs.

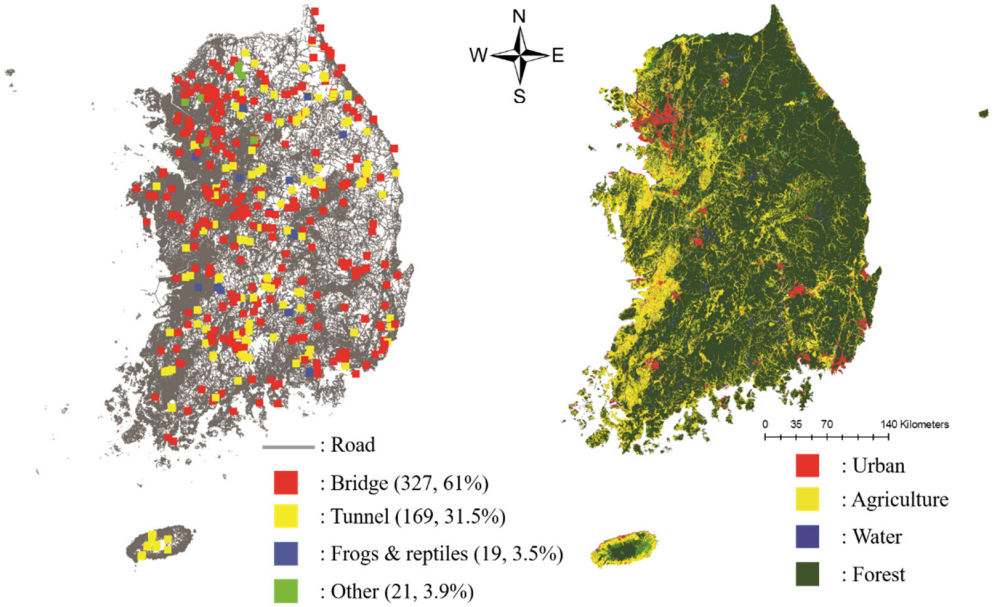

Figure 1. A map of roads (left) in South Korea (1 m resolution) and 536 eco-corridors (red: bridge type; yellow: tunnel type; blue: frog and reptile passage; and green: other). The map on the right shows land-use types in South Korea. Approximately 65% of areas are covered by forests (green). Red, yellow, and green indicate urban, agricultural, and water areas, respectively.

2.3. Comparison of Research Trends Using Text Mining Methods

We traced the Korean research trends in WVCs and compared them with international research trends because it is only recently that Korean research has begun to emerge on these issues. This comparison can provide information on the principal paradigms or knowledge domains for understanding roadkill in Korea, and emerging and high-impact international themes that might be introduced to domestic studies. To compare the domestic research trends with international trends, we collected peer-reviewed papers with publication dates from 1992 to 2022 from the core collection of Web of Science (https://mjl.clarivate.com/ (accessed on 21 November 2022)). From the articles searched with the terms, "roadkill" and "road-kill", the title and keywords were extracted to create a bibliometric visualization map. The analytical method for bibliometric visualization was supported by VOSviewer, which constructs a map based on a co-occurrence matrix of terms (items) and calculates item density and clusters [18]. As terms with a high relevance score tend to represent specific topics covered by the text data [19], each cluster was summarized with items with a high relevance score. A total of 433 items of international literature and 86 items of literature published by Koreans were used as the data source for this study. Before creating the maps, synonyms (e.g., roadkill and road-kill) were merged into a single term, and some keywords which were only in Korean were translated into English. After selecting the items based on the minimum number of occurrences, specific terms representing study sites (e.g., the Korean peninsula, Brazil) or types of papers (e.g., case studies and reviews) were manually excluded, and a set of connected items was displayed.

3. Results

Among the 86 articles related to WVCs, the number published has increased; those about eco-corridors have steadily increased since 1998. Mitigation system and roadkill articles have been published since the mid-2000s (Figure 2a). However, the volume of research on roadkill and eco-corridor was similar (roadkill: 41.3%, and eco-corridor: 39.1%, Figure 2b). Small volumes of articles about the law and other topics have been published.

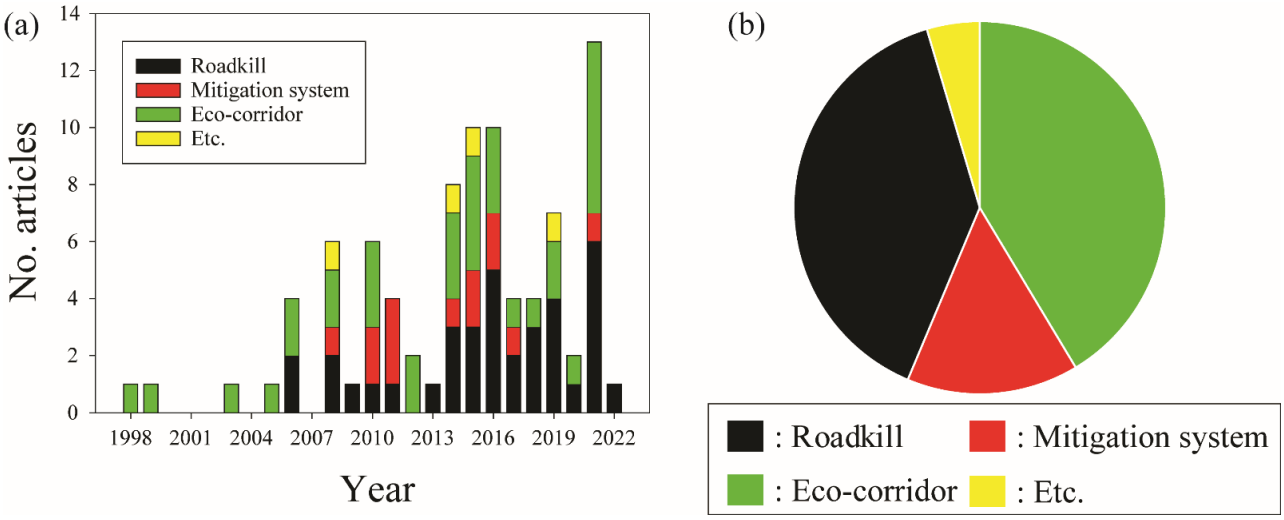

Figure 2. (**a**) The trends of the number of published articles related to wildlife–vehicle collisions (WVCs), and (**b**) pie graphs about the portion of the topic of the articles (black: roadkill, red: mitigation system, green: eco-corridor, and yellow: etc.).

3.1. Monitoring, Analysis, and Development of Monitoring Tools

Currently, there are two systematic roadkill monitoring systems in South Korea: the Ministry of Land, Infrastructure, and Transport; and the Korea Expressway Corporation (KEC), which monitors highways and roads [20]. For example, KEC monitors 37 road sections covering 4151 km [13]. Monitoring began in 2004, and the number of sections was 18. Since the monitoring length increased, the number of roadkill incidents decreased from 2436 in 2004 to 1560 in 2019 [13]. However, looking at the number of WVCs on highways and roads, the number has increased [21]. Korea National Park has also started monitoring roadkill near national mountains since 2006 [15]. Initially, 35 routes in the 15 national parks were monitored. As the new areas have been designated as national parks, the number of routes has increased (41 routes in 16 national parks in 2009, and 100 routes in 20 national parks in 2021).

Studies on roadkill have mostly analyzed the frequency related to seasons and land-use type near the event [22] (see also Choi and Park [23]). Min et al. [24] analyzed roadkill data between 2003 and 2007 in the Odae Mountain National Park. Lee et al. [25] investigated roadkill between 2003 and 2005. Kim et al. [13] analyzed the frequency of each species based on long-term data from the Korean Expressway Cooperation between 2004 and 2019. Although these studies focused on mammals, some studies focused on amphibians [26], and endangered crabs [27].

Some researchers have applied point analysis and modeling approaches. To explore roadkill hotspots, kernel density estimation and hotspot analysis (Getis-Ord Gi statistics) were applied [17]. Nearest-neighborhood analysis has also been used to define point distribution patterns [28]. Kang et al. [29] applied a graphical theoretical model to reveal the relationship between roadkill frequency and lack of landscape connectivity. In addition, based on bird data in Seoul metropolitan city, the complex networks of green areas are important as the total areas for sustaining biodiversity [30]. Kim et al. [31] applied graph modeling to reveal the spatiotemporal characteristics and predictions of leopard cats. Jang et al. [32] applied point-process modeling to investigate the characteristics of areas with a high frequency of roadkill events. Maxent modeling was used to reveal the characteristics of areas with high roadkill rates of endangered leopard cats and otters [33].

Roadkill monitoring systems have been developed. NIE has developed apps for recording roadkill events. Surveyors can upload pictures and coordinates. However, the app is not available to the general public; only surveyors are permitted to use it. A total of

2136 surveyors were permitted in 2019 [20]. DNA was used to identify the species and sex of carcasses [34].

3.2. Developing Wildlife-Vehicle Collision (WVC) Mitigation Systems

Since 2005, the KEC has implemented fencing to mitigate the roadkill rate [35]. The mitigation effects of the fences were evaluated after the policy was implemented. After fencing implementation, roadkill rates decreased to 60.8% compared with those before the implementation. As the fence is critical for mitigating collisions, appropriate fence heights were also evaluated. Although the heights can be more helpful in mitigating collisions, generalized linear mixed modeling based on behavior suggests how much height affects the target species' desire to jump [4]. Artificial paving patterns beside roads can deter wildlife from approaching roads. The rectangular type was more effective than the honeycomb type for Korean ungulates (long-tailed goral, water deer, and roe deer), whereas in the 3 m width, the goral and roe deer were more deterred by the honeycomb type than the rectangular type [36]. Chang et al. [37] selected the appropriate freeway median barriers on the road considering wildlife as well as humans. They suggested that flexible median barriers can be better than concrete barriers in countryside areas with a low frequency of traffic congestion (less than 30,000 cars/day) owing to the high density of wildlife. However, in urban areas with a high frequency of traffic congestion (over 80,000 cars/day), the already built concrete barriers can be better because barrier replacement where car density is high is very difficult, and the wildlife density is lower than that of the countryside. In parts of the countryside with a high frequency of traffic congestion (over 30,000 cars/day) or in urban areas with a low frequency of traffic congestion (less than 80,000 cars/day), they suggested the use of both types of barriers. When wildlife animals enter roads, exits can provide an escape pathway. Ryu et al. [38] also investigated appropriate unidirectional exits from roads for animals.

Some studies applied IT and used reusable energy to deter wildlife from crossing roads [39–41]. Jeong et al. [39] and Song and Lee [41] suggested deterrence systems based on the detection of wildlife approaching the fence, whereas Noh et al. [40] suggested methods to determine whether detection can affect both wildlife and drivers by sending the data to the car navigation system.

3.3. Studies on Wildlife Corridors

Since the first corridor was constructed in 1994, the number of corridors has rapidly increased. The volume of research about corridors has increased since the late 1990s. Kim et al. [42] pointed out the problem of fragmentation and the importance of building eco-corridors. In their paper, of 50 reports assessing the impact of regional road construction, only 4 suggested corridor construction [43]. Manuals for constructing corridors had been published in 1999 and 2003 [10,44]. However, researchers have raised problems about the manuals, which should be more developed. Kim [45] suggested the importance of multi-layered plantings in the corridors. In 2010, a more developed and detailed manual was published in accordance with the concerns raised about the previous manual [46]. Recent research has been conducted to suggest ways of resolving the conflicting needs of wildlife and vehicles in narrower areas. As the study areas are narrower, suggestions would need to be more detailed. Bang [21] suggested that barriers and corridors should be established within 10.1 km of Sejong city. Kim et al., [47] suggested where the corridors should be built according to wildlife animal movements and the cost of construction.

In Seoul's capital metropolis, there are 30 corridors. Recently, these corridors have not only been used for wildlife but also for trackers, being divided into two spaces (Figure 3). Thus, the evaluation of utilization by wildlife is becoming more critical because the spaces used by trackers can affect the behavior of wildlife [48,49].

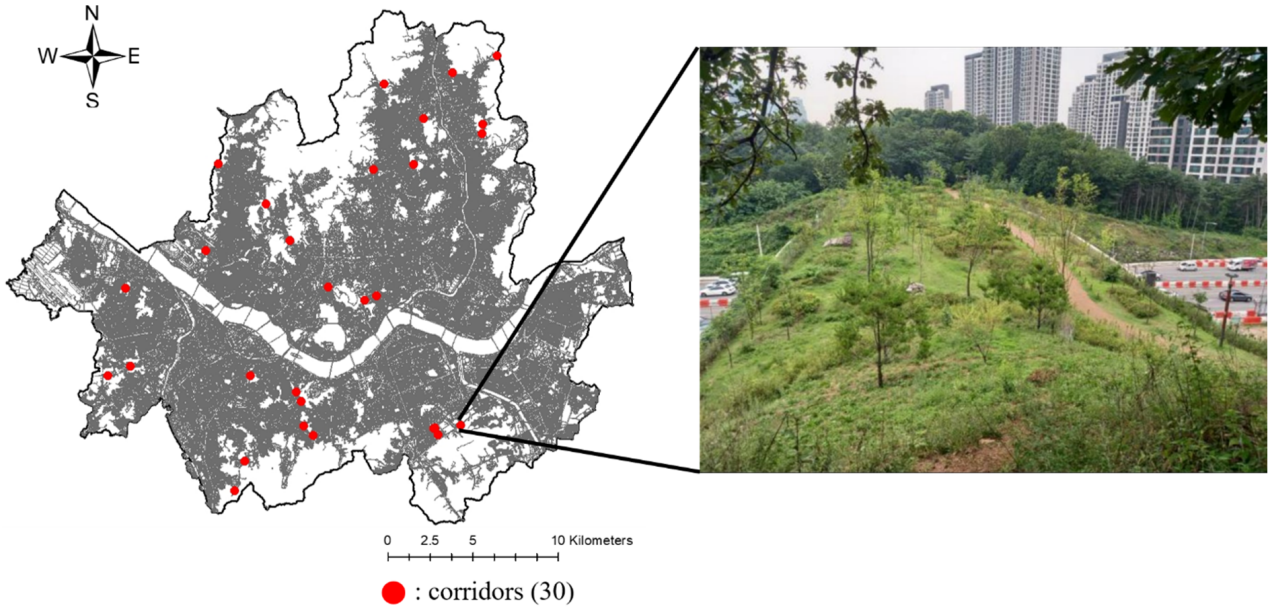

Figure 3. Thirty corridors in Seoul capital city (**left**) and a view of one of the corridors (**right**). The corridor consisted of passages for wildlife (covered areas) and trackers (uncovered areas).

Since 2016, the South Korean government has built an important eco-corridor in Choopuryeong, which is in the center of South Korea and surrounded by mountains (Figure 4) [50]. The area has been divided into highways, roads, and trails [51]. After construction, the frequency of occurrence of mammals, birds, and beetles increased. Wildlife animals can easily use corridors. The number of mammal species in the three eco-corridors was 14, 7, and 11, respectively, whereas the number of mammal species living in Choopuryeong was 17. A total of 142 individual beetles from 20 species were trapped in the eco-corridors.

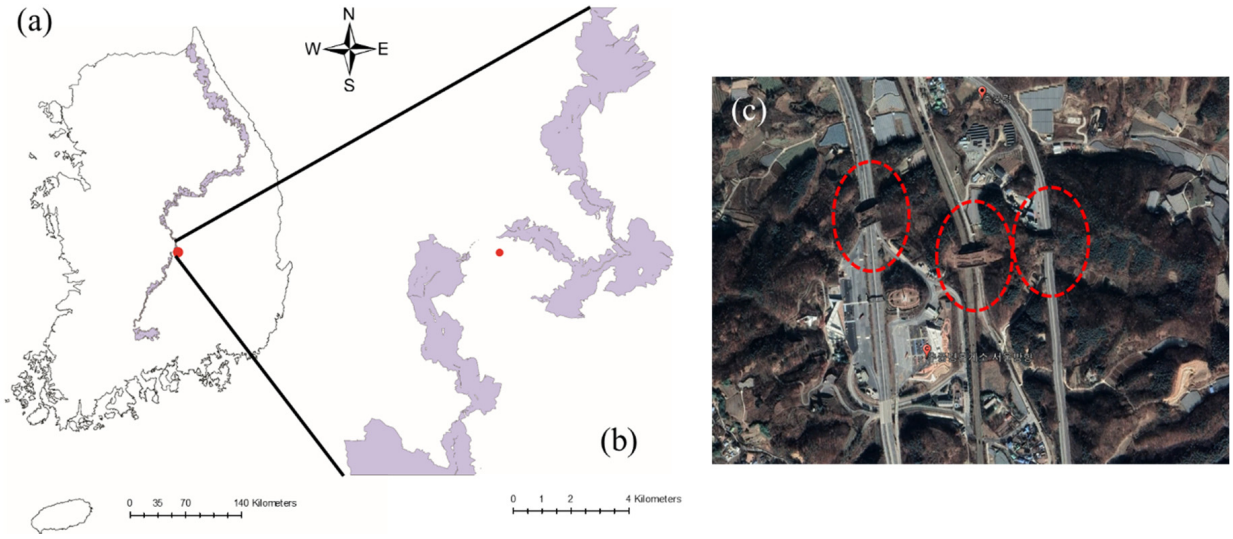

Figure 4. (**a**) The location and satellite imagery of the Choopuryeong eco-corridor (red dot) in South Korea. The left map shows the Baekdodeagan mountain range, the biggest mountain range, and the location of the eco-corridor. (**b**) the disconnection of the mountain by enlarging a portion of the map on the left. The red dot represented the Choopuryeong eco-corridor. (**c**) the satellite imagery of the corridors (circles). The corridors covered highways, railways, and regional roads.

National institutes such as the National Institute of Ecology and other academic researchers have investigated the rate of eco-corridor construction guidance and evaluated

the utilization rate by wildlife. The rate was 67.3% in the National Park, but 46.1% in the countryside. The average utilization rate in the 72 corridors was 1.3 uses per day [52]. Using GIS analysis tools, such as circuit modeling and morphological spatial pattern analysis, the areas were defined to connect the habitats [53]. The ratio between the width and length of the corridor was critical, and a value over 0.63 was recommended. Park et al. [49] focused on the utilization rate in relation to the type (tunnel, stepwise, arch, pipe, box, and bridge) and structure (closeness, width, length, plantation rate of the corridor, and habitat area around the corridor) of the corridors, and land-use patterns around the corridors. The results show that habitat area was the only critical factor. Lim et al. [54] also showed similar results, in which the habitat condition around the corridor and spatial complexity (pond, refuge, and similar plantation around the corridor) in the corridor were critical.

Some research has been performed concerning where to establish the corridor. Lee and Lee [55] suggested that, for carnivores, the corridors should be on roads beside forests and streams, and the underpass type could be more appropriate for forest and cultivated areas; while for herbivores, the corridors should be in the roads surrounding forests, and the over-bridge type was recommended. Sin and Ahn [56] suggested the best location by simulating the movements of five species using an individual-based model. Chung [57] studied the best location for amphibians using a genetic algorithm. Jeong et al. [58] suggested how to build forest roads to facilitate crossing. This research suggested slopes around the roads.

3.4. Comparison of Bibliographic Networks between International and South Korean Roadkill Studies

To compare the international and Korean research trends, keyword distributions are illustrated (Figure 5). Of the 352 terms from domestic articles and 2353 terms from international articles, 50 were extracted to visualize the network and the links between items. The most frequently observed term was "roadkill" in both domestic (30 times) and international articles (45 times). In domestic research, "conservation" (9), "wildlife" (6), and "management" (6) followed as frequently used items, and "ecological corridor", "design", and "fence" occurred at the same frequency (5). In international research, "road ecology" (78), "road" (67), "wildlife-vehicle collision" (58), and "road mortality" (45) followed as frequently used items.

In terms of research subjects, selected terms for domestic research included "water deer", "*Hydropotes inermis*", "wildlife", and "amphibian", whereas those for international research included "vertebrate", "invasive species", "mammal", and "bird". With respect to the analytical methods, selected terms for domestic research included "GIS", "KDE", "Graph theory", and "camera trapping", whereas those for international research included "citizen science" and "monitoring". In both domestic and international research, "express-way" and "highway" were located at the focal point on the map.

Domestic (Korean) and international papers were divided into seven and five clusters of related items, respectively. These clusters can reflect major research domains and are based on noun phrases with a high relevance score. Seven clusters for domestic research were summarized with the most relevant phrases, i.e., "development" (0.94), "wildlife passage" (0.64), "roadkill hotspot" (0.94), "*Hydropotes inermis*" (0.83), "graph theory" (1.33), "connectivity" (1.32), "camera trapping" (3.11), "ecological network" (3.11), "guideline" (1.59), "restoration" (1.43), "slope" (0.84), "land cover" (0.67), "national ecological network" (4.22), and "conservation" (1.44). Five clusters for international research were summarized with the most relevant phrases, i.e., "temporal pattern" (3.51), "habitat suitability" (2.11), "invasive species" (4.88), "COVID" (0.98), and "carcass persistence" (3.31).

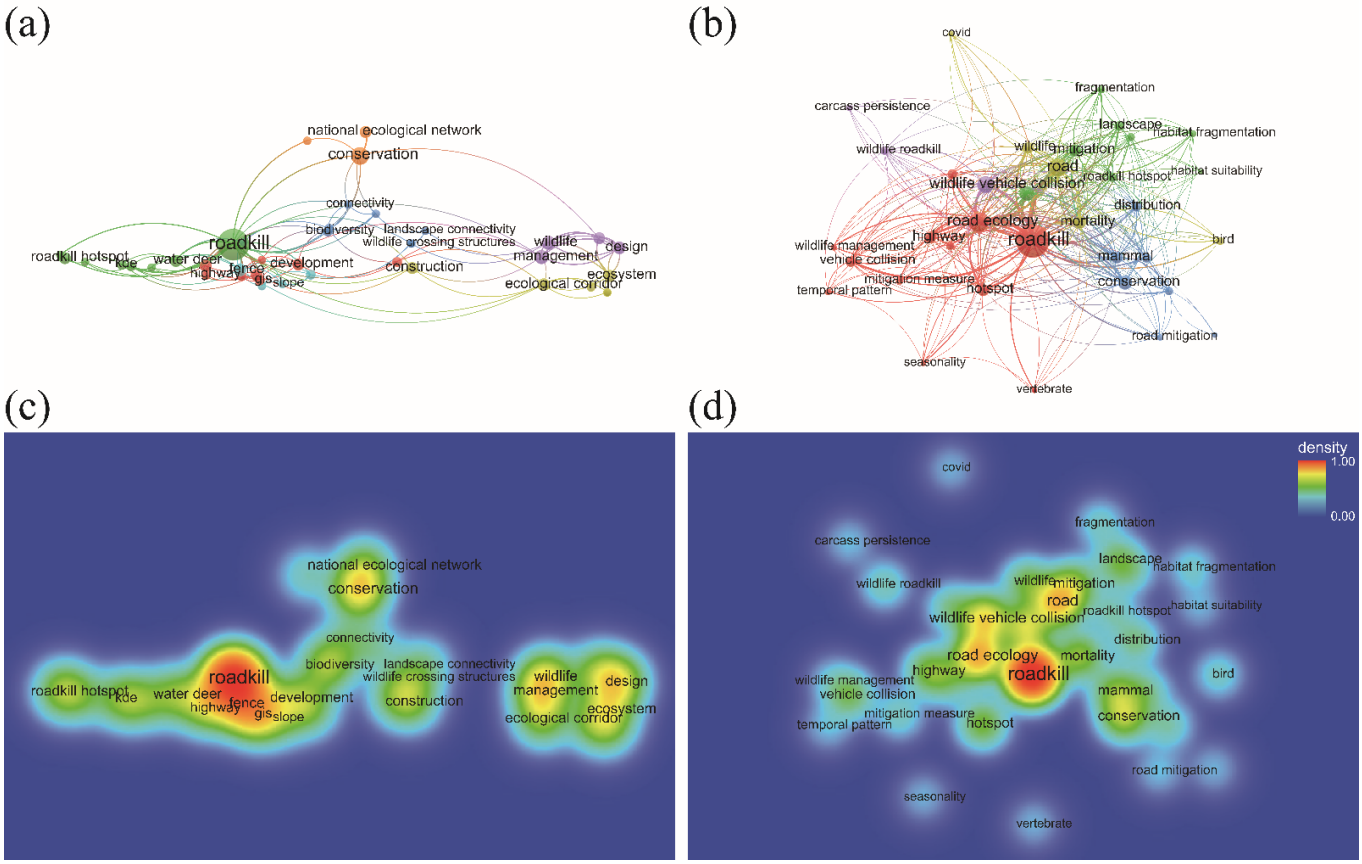

Figure 5. Network visualization maps of terms extracted from (**a**) domestic and (**b**) international research regarding roadkill and density visualization of terms extracted from (**c**) domestic and (**d**) international research. In network visualization maps, the size is proportional to the frequency of the terms, the color corresponds to the assigned clusters, and the links between the nodes stand for co-occurrence relation. In the density maps, the larger the number of items in the neighborhood of a point, and the higher the weights of the neighboring items, the closer the color of the point to red.

4. Discussion

In recent years, interest in the ecological effects of roads on ecosystems and landscapes has increased, as evidenced by several review papers published in scientific journals and edited volumes [59]. Reviewing the scientific literature about specific ecological topics on a national scale can suggest the shortcomings and future challenges that can broaden the research scope for the nation [60]. In addition, the history of research related to policy can provide examples for other countries. The present study is relevant because it shows how the WVC-related studies have been conducted during the relatively short rapid urbanization in South Korea. In the present study, we review Korean literature that is significant to this field and compare it with international trends.

We could largely separate the papers into three categories: (*i*) monitoring WVCs and modeling to find hotspots, (*ii*) developing WVC mitigation systems, and (*iii*) guidance and evaluation of eco-corridors. Since monitoring WVCs was established in 2005, methods and systems have been developed and survey areas have been enlarged [13]. The principal agencies engaged in monitoring have changed. Local and regional governments were agencies, but now the monitoring has come under the control of the institute related to environmental conservation. Now, an app-based monitoring system has been built.

Accordingly, modeling related to monitoring has been developed. GIS-based analysis, especially point analysis, has been more readily conducted. Also, defining the characteristics of WVC points has been explored. However, there are two points we wish to address. Firstly, although species distribution modeling has been one of the popular re-

search techniques worldwide to determine habitat characteristics and connectivity, as seen in the high-relevance habitat suitability (2.11) according to cluster results, little research has been performed. Few researchers who specialized in this field conducted and published work. Researchers who engaged with wildlife are lacking and need to be trained. Few professors who engage with wildlife allow the few researchers to broaden their scope. Secondly, the data-sharing system has been limited. Since monitoring started 20 years ago, big data cannot be analyzed without a project. Data can be shared with permission, but the permission has been restricted to a few permitted researchers or researchers who conduct their projects with agencies. This could also restrict research development, especially for modeling, which needs big data. The lack of researchers and sharing systems should be improved to develop this field further.

WVC mitigation systems have been tested and evaluated. Fence height to limit the roadkill rate, artificial paving patterns beside roads, appropriate freeway median barriers on the road considering wildlife, and evaluating unidirectional road exits for wildlife were among studies confined to road systems to mitigate WVCs. In addition, some ICT technologies have been applied to deter wildlife from crossing roads [39–41]. Because aspects considering mitigation are broad, trials to broaden all aspects are critical. A team from the NIE considering only WVC mitigation can allow broad aspects to be studied and systems to be developed. In addition, it was encouraging that other research groups concerned with WVCs, especially transportation, have studied and published some aspects of the systems. Because WVCs management can be multi-disciplinary, including ecology, transportation, and politics, further research collaboration with all engagers would also be needed [61].

Since alerts about WVCs had been issued in the late 1990s, policies to reduce them have been suggested and promoted. The first eco-corridor was built in 1999, and now 536 corridors have been built. The pace at which the number of corridors is increasing could be one of the fastest in the world. As awareness of WVCs has increased, related research has been conducted to improve ways to implement corridors or limit these events.

Despite the research conducted, some corridors have been made without considering wider aspects. In some corridors, a steep slope at the end does not allow animals to cross. Currently, in metropolitan cities, corridors have been built to connect green areas for trackers without considering wildlife animals. This could have resulted from a lack of consultation between the government, transportation workers, and ecologists. Different departments are not allowed to engage with all aspects of policy. Data-sharing may also be difficult because of the different research associations. Because of the large number of studies being increasingly conducted, facilitation with fluent communication between each participant could be one of the most important factors to improve the situation to limit WVCs in South Korea.

After reviewing 51 domestic, 15 international papers, 19 reports, and 1 thesis, the topics have become more diversified. Broadly, research testing mitigation systems, monitoring and analyzing roadkill incidents, and evaluating eco-corridor systems has been conducted. However, research on road ecology theories remains rare. As most studies were based on the Korean situation, the results from the studies would not be useful or applicable to a broad audience related to the fields.

Comparing the research associations between international and Korean society, the structures of Korean society are more disconnected and less dispersed (Figure 5). In addition, the keywords are narrower than studies from international society. While the keywords from South Korean studies were specific species names or regarding topics such as fences, the common keywords from international studies were broad and the main terms related to understanding roadkill events for example, road ecology and conservation. This means that there is room for research related to roadkill to be developed in South Korea. As the volume of research increased, the common keywords could be main terms for subjects such as road ecology, roadkill, and conservation [62]. Accordingly, research

answering the hypothesis related to landscape connectivity and road ecology remained scarce in South Korea.

As the number and scope of research projects conducted in South Korea have increased and broadened, studies could be more rapidly developed in the future. Various aspects of research to mitigate WVCs have been explored. Appropriate freeway median barriers in the road and deterrence systems such as artificial paving beside roads are new trials to apply to Korean conditions. As the national institute conducts research and reports annually, and the subjects and aspects of research from the university have been broadened and diversified, research resulting in conflict mitigation will increasingly contribute to society.

5. Conclusions

Since South Korea has experienced rapid urbanization, research about WVCs has been increasingly conducted and developed, although the studies have started relatively recently. The research topics about roadkill monitoring, mitigation system development, and eco-corridors have been broadened and developed. However, the number of researchers remains low, and systematic problems such as inadequately connected networks between researchers engaged in WVCs and data-sharing also remain. As interest and concerns about WVCs increases and become popularized, and systems become more mature, research related to policies will be able to minimize the number of WVCs in the future.

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