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Review

Biodiversity and Transportation Infrastructure in the Republic of Korea: A Review on Impacts and Mitigation in Developing the Country

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Abstract: The construction and continued use of transportation infrastructure, specifically roads, has had a significant global impact on biodiversity and the environment. The Republic of Korea, or South Korea, has a road density of 1.13 km/km^2. So far, three nationwide studies about vertebrate road-killed species have been reported, showing bias towards medium to large mammals, the most common victims being the Korean water deer (*Hydropotes inermis*), Korean hare (*Lepus coreanus*), Siberian roe deer (*Capreolus pygargus*), and the common raccoon dog (*Nyctereutes procyonoides*). Road-kills, or wildlife-vehicle collisions (WVCs), tend to occur in or near preferred habitat types or in highly fragmented areas, with roads additionally being linked to habitat fragmentation and loss. Alongside WVCs and habitat effects, information about other adverse effects on biodiversity is scant, although there are reports that heavy metals and other pollutants from road runoff impact marine biodiversity, vegetation, soil, and groundwater. Furthermore, roads have been linked to a prevalence of invasive plant species. To mitigate road impacts, the South Korean government has constructed, with mixed results, 530 wildlife crossing structures, mainly including overpasses and tunnels. To mitigate road impacts more effectively, the country will need more construction, monitoring, and consistent management of wildlife crossing structures. Further, incorporating plans for wildlife crossing structures in early stages of road development will be required.

Keywords: South Korea; biodiversity; road kills; road effects; wildlife-vehicle collisions

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1. Introduction

Transportation infrastructure, notably the construction and use of road networks, has a well-documented impact on biodiversity around the world [1–3]. These impacts can range from abiotic to biotic to ecosystem impacts, which are largely considered to have negative effects on biodiversity [1]. Particularly, infrastructure may contribute to biodiversity loss through disturbance and fragmentation [3]. The full range of these effects can be observed in regions with developing infrastructure, particularly in the tropics, where biodiversity is high, as species respond to changes in land use and new sources of potential mortality [4,5]. Such regions also face challenges to develop mitigation of biodiversity loss alongside transportation infrastructure [6], where economic growth may be favored over environmental protection [7].

Roads can impact the environment in a variety of ways [1]. Abiotic effects include changes to physical and chemical properties of soil and water, as well as noise pollution. Road effects on fauna and flora include mortality through wildlife-vehicle collisions (WVCs), or road kills, and as a corridor by using roadsides for movement. Finally, whole ecosystem effects include habitat loss and fragmentation and road-edge effects. The present review will largely focus on wildlife mortalities and barriers to movement caused by roads and landscape change and fragmentation. For example, habitat destruction, fragmentation, and environmental degradation partially due to roads have been linked to amphibian declines [8]. Specifically, most species are negatively affected by high road density and resulting poor water quality. Roads have also had negative impacts on mammals and larger, threatened species, such as the Amur tiger (*Panthera tigris altaica*), whose survival was significantly reduced in areas with primary or secondary roads [9].

Because of these negative effects, mitigation is crucial for biodiversity conservation. Effectiveness of wildlife crossing structures is dependent on road preconstruction planning, habitat connectivity, road permeability, financial expense (more effective solutions are often more costly), and post-implementation monitoring [10]. In the past, there has been little foresight to monitor wildlife pre-construction of roads, and therefore studies on pre- and post-construction biodiversity are limited, but continued research on road effects indicates that before-and-after monitoring is crucial for mitigation and biodiversity conservation [11]. Wildlife crossings, such as overpasses or underpasses, become more effective from input of expert opinion and knowledge of local wildlife [12]. For example, the distance of road to forest vegetation is negatively correlated with WVCs, meaning collisions are more likely to occur where forest is close to the road [13]. Therefore, these areas would be the ideal places for corridors as it would reduce collisions where connectivity matrix is already less fragmented.

The Republic of Korea, hereafter South Korea, provides an interesting case of a country with a developing transportation infrastructure. A large portion of the country's population occurs in large, highly-developed cities, such as Seoul or Busan, while a diminishing and aging population remains in underdeveloped rural areas [14]. Nevertheless, efforts to revitalize rural areas of the country and interconnect some of the larger cities have resulted in growing and modernizing roads and highways. More recent concerns over ecology and maintaining biodiversity have led to monitoring and mitigation of road development effects on wildlife, but this often becomes secondary to the economic and social benefits provided by such development. In terms of biodiversity, South Korea provides habitat to a large number of species relative to its size of 99,713 km^2. Currently, there are 50,827 species recorded in South Korea, including 7833 plant species and 29,678 animal species, of which 1995 are vertebrates [15]. Additionally, 2289 species are endemic to South Korea, 267 are nationally endangered [15], and 185 are classified as "threatened" by the IUCN [16]. Currently, there are 3467 protected areas covering 16.97% (16,917 km^2) of terrestrial ecosystems and 2.46% (7979 km^2) of marine and coastal ecosystems [17].

To elucidate the relationship between transportation infrastructure and biodiversity in South Korea, this review will (1) summarize recent transportation infrastructure development in the country, (2) compile the major research in the country, focusing on impacts of such infrastructure development on biodiversity, and (3) examine mitigation policies and practices present in the country. Major research will be broken down into (1) the role of roads in WVCs and as barriers to dispersal, (2) habitat fragmentation and loss due to roads, and (3) other impacts, such as abiotic effects.

2. Infrastructure Development in South Korea

Following the end of the Korean War (1953), South Korea has undergone various stages of developing their infrastructure in attempts to industrialize and build a competitive economy. After the Korean War left the country with a crumbling and insufficient road system, the period between 1953–1961 saw infrastructure reconstructed [18]. Expansion of transportation infrastructure occurred between 1962–1971, wherein railways and highways were built across the country, including four major highways built during this time. The Gyeongbu Highway, connecting Seoul to Busan, opened in July 1970 as a way to modernize and industrialize the country [19]. During construction, the focus was simply to complete the highway, with no consideration as to its effect on biodiversity. Since the late 1960s, 97,253 km of roads, including 2778 km of expressways, have been constructed [20]. There are a total of 112,977 km of roads existing in the country today, of which 4848 km are national expressways and 14,098 km are national highways [21]. The total road length in the country translates to a road density of 1.13 km of road per km^2. Urbanization since the 1970s has resulted in a population shift towards larger, more urban areas, leaving an aging population in rural areas behind [14]. More recently, there has been a governmental push to revitalize agriculture and rural areas in the country through improving transportation and accessibility [22]. This includes, for example, the Comprehensive Rural Village Development Program, which is meant to strengthen competitiveness of the agricultural sector and rural areas and improve quality of life [14].

3. Impacts of Infrastructure on Biodiversity

3.1. WVCs and Barriers to Movement

In the Republic of Korea, WVCs are by far the most researched aspects of infrastructure effects on biodiversity and the environment. So far, three nationwide studies have been conducted and made accessible through publication, which have surveyed all vertebrate road-killed species. The first, conducted between 1996 and 2003, along one national highway by independent researchers, recorded 860 WVCs (average 123 ± 157 per year), of which 165 were Korean hares (*Lepus coreanus*), 146 were common raccoon dogs (*Nyctereutes procyonoides*), 146 were Eurasian red squirrels (*Sciurus vulgaris*), and 90 were Korean water deer (*Hydropotes inermis*) [23]. Between 2008 and 2012, 10,940 WVCs were recorded (average 2138 ± 203 per year) across high-speed national highways (overseen by the Ministry of Land, Infrastructure, and Transport), with Korean water deer comprising the majority of WVCs at 79.7% [24]. In June 2018, the Korea Road-Kill Observation System (KROS) was launched to collect observation of WVCs in the country through an application released to road maintenance workers [25]. Through this application, road menders take pictures of road-killed animals that they encounter, which are then sent to professional wildlife researchers for identification. Over 15 months (2018–2019), observations resulted in the recording of 5812 WVCs entered into the KROS, of which the majority were made up of five common mammal species: Korean water deer, domestic cats (*Felis catus*), Siberian roe deer (*Capreolus pygargus*), common raccoon dogs, and domestic dogs (*Canis lupus familiaris*). However, the website for the database no longer appears active. WVC surveys can serve as indicators of faunal communities. Comparison of these nationwide studies across time highlights potential declines of both Korean hares and Eurasian red squirrels in the country and supports either national or international designation for both species. Particularly, the Korean hare has been recommended for monitoring and as a potential endangered species candidate as population trends are unknown [26].

In addition to nationwide WVC surveys, more targeted surveys have focused on WVCs within smaller regions of the country and WVCs of individual species or taxonomic groups. A study conducted around Jiri Mountain National Park between 2004 and 2006 on the nine most prevalent mammal species examined land use type within 300 m of WVCs [27]. Among 1279 WVCs, WVCs were the highest for all species near grasslands; WVCs of Eurasian red squirrels, Siberian chipmunks, and Korean hares were higher near forests; and WVCs of common raccoon dogs, Korean water deer, and leopard cats (*Prionailurus bengalensis euptilura*) were higher near rice fields. These results roughly correlate with foraging and predation patterns and preferred habitat. In a separate study of the same locality during 2004–2007, 5044 instances of WVCs were observed for all vertebrate species [28]. WVCs were influenced by water and rice paddies, low traffic volume, high percentage of vegetation, and a lack of road features that provide protection or alternative passage for animals. Additionally, GPS tracking suggests that road barrier features, such as median strips, guard-rails, fences, and boundary blocks, did not deter wildlife from crossing [29].

Although WVCs are a potential cause of wildlife declines across vertebrate taxa, studies targeting snake WVCs are limited. Among a total of 155 occurrences observed from 2007–2012, snake WVCs were more frequently found in mountainous areas along transitions between environments [30]. Deer collisions pose a threat to safety, especially on Jeju, which has a high volume of tourists. Between 2014 and 2017, summer and autumn had the highest numbers of collisions [31]. Mitigation may include road fencing and signs to warn of collisions and enforce speed limits. Between 2002 and 2012, 30 cases of threatened fairy pitta (*Pitta nympha*) casualties were examined, with 50% of causes being human-related, while 10% were from vehicle collisions [32].

In a study of WVC frequency for leopard cats in South Korea, a statistical analysis showed that the frequency was most highly correlated with traffic volume, where frequency increased with decreasing traffic volume [33]. Patch connectivity was also significant in the model, although negatively correlated with WVC frequency. WVC abundance in South Korea has also been found to correlate to habitat connectivity of other mammal groups. When WVC abundance was compared to habitat connectivity in small, intermediate, and large mammals in South Korea, WVCs were found to be highly correlated with high connectivity at scales respective of the mammals' size groups [34]. In addition to being potentially fatal to crossing wildlife, roads present barriers to movement of animals, such as the Asiatic black bear (*Ursus thibetanus*), which has significant road barriers across their potential range in the Baekdudaegan Mountain Reserve [35]. Therefore, wildlife corridors are needed in targeted areas of habitat and least-cost pathways in order to reduce WVCs. The urgency of such action is supported by the fact that these bears are already beginning to disperse from the national park of their initial reintroduction [36].

3.2. Habitat Fragmentation and Loss

As in countries around the world, the construction and continued use of roads in South Korea contribute to habitat loss and fragmentation, which reduce biodiversity [20]. The most fragmented area lies along the Baekdudaegan, with an estimated 987 fragmented patches along its length and surrounding area [37]. In a 2002–2003 study of 12 mammal species at nine sites along the Baekdudaegan mountain range, Korean hares and wild boars (*Sus scrofa*) consistently used areas 50–100 m from roads, while Eurasian red squirrels (*Sciurus vulgaris*) and Siberian weasels (*Mustela sibirica*) were more observed within 50 m of roads [38]. This implies that further fragmenting of habitat by road construction may reduce habitat and therefore population of Korean hares and wild boars. Habitat suitability modelling for wild boars has shown that although suitability is negatively affected by road distance, roads cross large portions of highly suitable wild boar habitat [39]. Korean field mice (*Apodemus peninsulae*) are also negatively affected by road presence compared to striped field mice (*Apodemus agrarius*), the former requiring interior forest for its habitat [40]. Further evidence of negative impact of roads on wildlife is that Korean water deer riparian crossing and habitat suitability are negatively affected by one-lane road density [41] and distance to road [42], respectively, while leopard cat habitat suitability is negatively affected by two-lane road density [41]. Generally, cut slopes of forest roads can also affect wildlife movement in mountainous, forested areas [43].

While roads in South Korea have a well-documented negative impact on mammal habitat in particular, species, such as reptiles and amphibians, are also affected by habitat loss and fragmentation caused by road construction [20]. Development and construction of paved roads has led to habitat loss and fragmentation for the Suweon treefrog (*Dryophytes suweonensis*), a threatened treefrog endemic to the Korean peninsula. Habitat suitability modelling shows that habitat suitability for the species decreases in smaller habitat patches and patches that are highly fragmented, with higher suitability found further from paved roads [44]. The same effects can also be assumed for the closely-related yellow-bellied treefrog (*Dryophytes flaviventris*), a recently described treefrog species with a restricted range in southern South Korea [45]. This species also faces an imminent threat of the complete loss of habitat for one of its largest populations through the construction of a proposed bypass [46,47].

3.3. Invasive Species

As in other countries around the world, roads in South Korea have been linked to a prevalence of invasive species in roadside plant communities [48]. For one invasive species in particular, the distance of common ragweed (*Ambrosia artemisiifolia* var. *elatior*) to roadsides was found to be the third highest contributor to the species' distribution, which was highest closer to roads [49]. This is also true for the citrus flatid planthopper (*Metcalfa pruinose*), whose distribution is strongly linked to roads and urbanization [50]. In the case of invasive insects, such invasions can not only lead to reduced biodiversity of natural ecosystems but can also have significant impacts on agriculture. Roads and other anthropogenic development activities that lead to land-use change have been known to exacerbate the spread of the invasive American bullfrog (*Lithobates catesbeianus*) [51], which is a problematic invasive species in South Korea [52].

3.4. Other Impacts

Although WVCs and impact on habitat are the most-studied effects of roads in South Korea, there are several other notable impacts of roads and traffic. For instance, roads exacerbate air pollution from cars [20] and contribute to global warming [20] and sound pollution [37]. Further, pollution by heavy metals, such as platinum, has been traced to roads, especially in cities like Seoul [53] and Busan [54,55]. These heavy metals and other pollutants from road runoff impact marine biodiversity [54], vegetation [20,53], soil, and groundwater [20]. Furthermore, creation of roads and the resulting fragmentation, erosion, and hydrologic changes have resulted in an increase in natural disasters, such as avalanches and flooding [20].

3.5. Special Cases

In addition to widespread, generalized effects of infrastructure on biodiversity, there are two special cases of note that have current or potential future impacts on biodiversity: the Saemangeum land reclamation project and the Korean Demilitarized Zone (DMZ). Saemangeum, completed in 2010, was a project involving the construction of a massive seawall on the west coast of South Korea and the filling of an important estuary to "reclaim" land for agricultural use and attempt industrialize North Jeolla Province. Although it did not primarily focus on transportation infrastructure, the Saemangeum land reclamation project was intended to revitalize and develop rural parts of the country and demonstrates a common issue in the country of favoring economic development to the detriment of the environment. This large-scale development project, which has done little to improve the lives of local villagers [56], has been catastrophic to local shorebird populations, displacing around 130,000 individuals of 20 species of shorebird, for which the affected estuary system was an important habitat along migration routes [57]. A total of 48 shorebird species have been affected by the project, wherein there has been an overall decrease in shorebird abundance by 95–97.3% [58].

Although such past projects have been detrimental to biodiversity, the country has a rare opportunity with the Korean DMZ. Transboundary lines present unique environmental issues, as bordering countries may have drastically different conservation management strategies [59]. Since development and human activities have not been possible within the 4 km wide, 250 km long demarcation line since 1953, the area has become a sort of haven for biodiversity, providing habitat for 4432 species overall [60], including threatened red-crowned (*Grus japonensis*) and white-naped cranes (*Grus vipio*) [61]. If not designated as a protected area in the potential reunification process, this important habitat will likely become degraded and fragmented through the construction of roads and industry [62]. It is therefore critical that the two countries–North and South Korea–work together to address biodiversity conservation. The creation of an ecologically sound "peace park" could even become a point of pride in unification of the two countries [63].

4. Mitigation of Road Impacts

4.1. Wildlife Crossing Structures and Their Effectiveness

Implemented effectively, wildlife crossing structures can solve problems of WVC mortalities, habitat fragmentation, and connectivity. Between 1998 and 2015, government agencies in South Korea built more than 317 wildlife crossing structures [28], with 98 more built through 2018 (415 structures [64]), culminating in a current total of 530 structures (National Institute of Ecology Korea). This includes 323 overpasses, 165 tunnels, 19 amphibian and reptile passages, and 23 passages classified as "other" (Figure 1). Guidelines for wildlife crossing structures by the Ministry of Environment Korea include 14 guidelines for overpasses and 11 for underpasses. For overpasses, the compliance rate was found to be greatest for "soil depth over 70 cm for stable growth of plants" (88.2%) and lowest for "installation of an escaping facility in the drainage" (9.8%). For underpasses, the highest compliance rate was "appropriateness of locality to connect habitats" (81%) and the lowest rates were "installation of small ditches for amphibians and reptiles" and "attachment between wildlife fences and underpasses" (both 47.6%) [64].

The conclusion of a 1-year study monitoring 14 overpasses in Gurye county [66] was that there was a sufficient number of passages for wildlife in the area, although there was a high number of WVCs. This study suggests that WVCs of mammals and habitat fragmentation could be reduced by installing wildlife fences for safety and mitigation, although this of course contrasts with results of GPS tracking of individuals, which shows that such structures do not actually deter crossing [29]. While crossing structures in the country indeed reduce the number of WVCs, other studies have found that actual use of such passages are insufficient for wildlife crossing because of location, management after installation, structure, and vegetation [67]. For instance, overgrowing vegetation may be enough to deter some species from using wildlife crossing structures [68]. Insufficient passages may even result in local extinctions of species, as demonstrated through a population viability analysis of Korean hares, common raccoon dogs, and Korean water deer, where there was only a 4% chance of survival for both Korean hares and raccoon dogs after 100 years [67].

Recent research has looked to improve mitigating effects of wildlife passages. Ecological models, such as habitat suitability indices, can efficiently identify localities for wildlife passages that maximize mitigation [69]. For example, wildlife passages implemented in less fragmented areas are more effective as crossing structures [70]. For wild boars, for which some roads still cross suitable habitat, passages can be constructed within high habitat suitability areas to improve connectivity [39]. Further, specific animals are needed as targets for wildlife passages [71], such as Korean water deer [66], which experience the highest country-wide rate of WVCs. While small- to medium-sized carnivores are able to utilize any type of crossing structure, water deer mainly cross under bridges [72]. In the case of reptiles and amphibians, whose WVCs are relatively understudied in South Korea [30], tunnels can effectively mitigate mortalities for many species, although some taxa, such as hylid treefrogs, largely avoid these, their only mitigating structure being overpasses [73]. Structures targeting avian species should also be considered [74]. Finally, it is suggested that wildlife passages are planned in the early stages of new road construction projects to maximize effectiveness and minimize periods of habitat disconnect [71].

4.2. *Proposal for Policy*

A continuing problem for conservation in South Korea is a lack of understanding of human activity impacts on the environment and biodiversity. In the case of Jiri Mountain National Park, it is suggested that more eco-friendly routes, such as bike trails, be constructed in lieu of roads [20]. Deliberate evaluations of environmental effects are needed after construction, as is policy to inhibit any kind of development in conservation areas. Currently, future development is prohibited in national parks in South Korea but maintenance of existing structures prior to national park designation is allowed. However, more successful biodiversity conservation would require removal of some of the more obstructive structures and limiting access to national parks [20]. Finally, biodiversity conservation would benefit from consistent management of national parks and other conservation areas. One proposal targets a particular species: the Asiatic black bear. This proposal for reconstruction of an ecological axis would involve soundproof walls and implementation of a WVC prevention system [37]. As of 2017, the proposed eco-friendly soundproof walls have been designed, test-installed, and monitored along Gyeongbu Expressway, north of Jiri Mountain National Park.

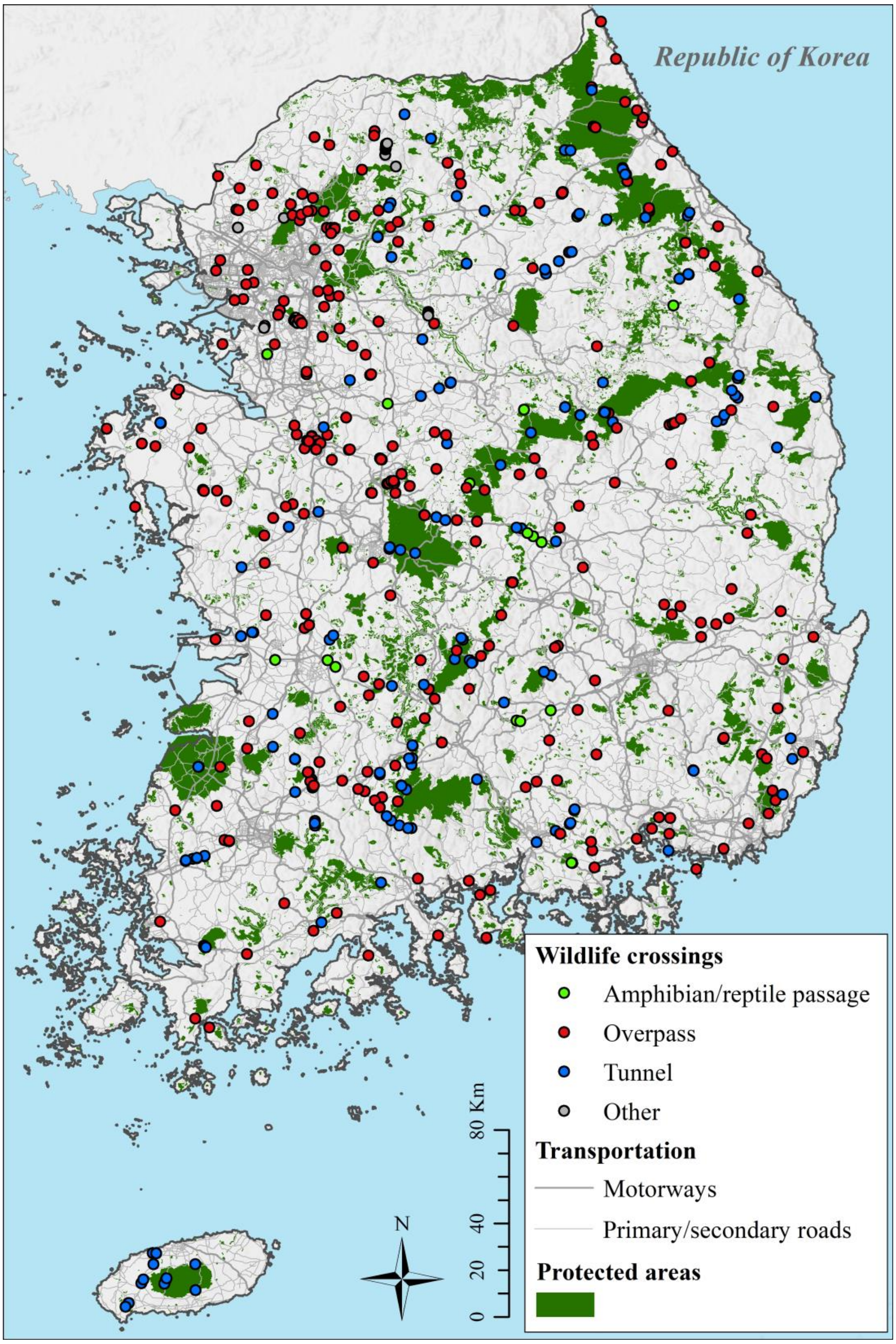

Figure 1. Map of the Republic of Korea with wildlife crossings and transportation. Wildlife crossing data provided by the National Institute of Ecology Korea (NIEK; available at: https://www.nie-ecobank.kr/wildlifecrossing/mapservice/MapserviceList.do (accessed on 6 July 2021)). Transportation data provided by OpenStreetMap contributors [65] (available at: https://www.openstreetmap.org (accessed on 16 July 2021)). Protected areas downloaded from Protected Planet [17] (www.protectedplanet.net (accessed on 10 May 2021)).

Aside from national park management, more care needs to be taken by the government to ensure compliance of roads and highways to environmentally friendly solutions. One potential solution would be to transition to rail travel, which would reduce the load of highway traffic [20]. Other solutions that would either improve biodiversity, reduce greenhouse gas emissions, or both include geometric and cross-section road designs were included in a proposed 'green network road construction method' [75]. Geometric road designs are aimed at efficiently designing roads to reduce emissions (reducing traffic times, reducing overall distance of travel), while cross-section designs include green areas adjacent to roads or along median strips (absorption of greenhouse gases).

5. Conclusions

In this review, we have demonstrated that the development of transportation infrastructure in South Korea has affected biodiversity directly through WVCs, habitat fragmentation and loss, and invasive species and indirectly through abiotic alterations to the environment. WVCs are the most researched effect of roads in South Korea; however, there are other notable impacts, such as habitat loss, fragmentation, and pollution of air, soil, and marine environments. As development continues in the country, researchers have suggested various methods for mitigation by using tunnels and overpasses. Since the beginning of modernized transportation infrastructure in South Korea, there has been a large disconnect between economy and environment as green planning was completely absent from most infrastructure development plans and analysis [76]. However, this has begun to change, with a recently announced "Green New Deal" plan, originally a COVID-19 response, a main focus of which is a green transition for infrastructure [77]. This proposed plan includes restoring terrestrial and marine ecosystems and transitioning to electric vehicles, away from diesel and gas.

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