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Research article

Evaluating the effectiveness of mitigation measures in environmental impact assessments: A comprehensive review of development projects in Korea

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ABSTRACT

Rapid urbanization and development projects in Korea have posed significant threats to biodiversity; thus, effective mitigation measures are required to preserve natural habitats. Nevertheless, the factors underlying variations in mitigation measure effectiveness according to the disturbance level and surrounding environmental conditions have not been clarified. This study evaluated the effectiveness of mitigation measures implemented in environmental impact assessments (EIAs) of development projects in Korea, with a focus on their effectiveness with respect to the disturbance level and surrounding environmental conditions. A review of 288 EIA reports from selected projects that implemented all 10 mitigation measures classified according to the Wildlife Conservation Comprehensive Plan was conducted. Using the biodiversity tipping point framework, the effects of mitigation measures on biodiversity were categorized into four levels and analyzed. Analysis of variance and redundancy analysis were then performed to discern the variance in mitigation measure effectiveness in terms of the disturbance level, surrounding environment, and species. The results revealed significant variations in the effectiveness of mitigation measures depending on the surrounding environment and disturbance level. Linear projects exhibited a clear impact on various species as the disturbance level increased, whereas area-based projects did not exhibit such pronounced effects. All species demonstrated a negative relationship with development duration, development area, and distance from urban centers. Notably, avian and amphibian species showed a strong negative correlation with the digital elevation model while reptiles and mammals exhibited a strong positive relationship with pre-development biodiversity and distance from protected areas, respectively. Mitigation measures play a key role in alleviating the adverse effects of development projects; therefore, our findings indicate the need for spatially tailored mitigation plans to augment their effectiveness.

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1. Introduction

The Kunming-Montreal Global Biodiversity Framework emphasizes that biodiversity loss should be halted, and biodiversity recovery should be promoted by 2050, and it outlines four core strategies and 23 action targets to be achieved by 2030 [1]. Aligned with these global directives, South Korea confirmed its commitment to these goals through the National Biodiversity Strategy 2030, which promotes the establishment of various policies and initiatives aimed at recognizing the value of biodiversity and ensuring its conservation and sustainable utilization [2]. This national strategy encapsulates specific goals and action plans to halt biodiversity loss by 2030 and restore biodiversity by 2050 [3].

To achieve these objectives, the Korean government is exploring the implementation of environmental impact assessments (EIA) [4], which have been instrumental in pre-emptively identifying and mitigating the impacts of development projects on biodiversity [5]. The current EIA procedure involves expert consultations, committee reviews, and public opinion aggregation, culminating in the evaluation and approval of the EIA by designated authorities [6]. However, the absence of guidelines and legal requirements for mitigation planning indicates a scope for improvement. Most EIA described natural environmental assets, flora, and fauna, the latter of which are detailed in mitigation plans based on the impact predictions of development projects [7]. These plans are reviewed during the EIA consultation phase, during which the feasibility, effectiveness, and practicality of the plans are assessed, and improvements are recommended where necessary. The submission of environmental statements has increased from 4,987 in 2010 to 185,390 in 2018, which reflects the increasing engagement in the EIA process, although the efficacy of these mitigation plans has not been confirmed (https://www.eiass.go.kr). Despite the increasing popularity of mitigation planning, South Korea's environmental assessment performance remains among the lowest among the Organization for Economic Cooperation and Development.

Previous research on biodiversity conservation, particularly in the context of mitigating the negative impacts of development projects, has provided a fundamental understanding of the impacts and proposed strategies to improve the effectiveness of mitigation plans [8]. These studies have significantly contributed to the evolving discourse on biodiversity conservation in the context of rapid urbanization and infrastructural development, and they have primarily focused on the allocation of adequate resources to ensure the success of mitigation measures.

For example [9], highlighted the need to allocate appropriate budgets to ensure the efficacy of mitigation plans, further emphasizing the importance of stakeholder collaboration and communication and advocating for educational initiatives to foster a better understanding and implementation of mitigation measures. Comprehensive and tangible mitigation plans appear to be lacking, which has led to uncertainty in their actual implementation and effectiveness. [10] proposed that a robust monitoring system to assess the success of mitigation measures and a flexible approach to modify measures are essential for increasing the effectiveness of mitigation plans. [11] advocated that indicator-based approaches, system diagrams, simulation modeling, and ecological modeling should be advanced to enhance the effectiveness of mitigation plans. They further emphasized the need to collect data on ecosystem recovery time, diversity, and abundance for better mitigation planning and implementation.

Several studies have investigated the application of long-term monitoring of select post-completion sites to evaluate the effects of mitigation measures on ecological corridors using before-after-control-impact analysis techniques to assess the effectiveness of biodiversity conservation policies and mitigation plans [12,13]. Additionally, several studies have utilized landscape connectivity, the incidence function model, and species distribution models to predict the impacts before and after development, providing foundational data for formulating appropriate mitigation plans within EIA [14,15]. These studies primarily focus on examining why the implementation rates of mitigation plans in EIAs are low and what institutional changes are necessary for improvement. They also introduce how quantitative assessment techniques can be utilized in EIAs, yet there is a notable deficiency in the analysis of how significantly, and due to which environmental factors, the performance of mitigation plans varies [16,17]. This knowledge is crucial for implementing appropriate mitigation plans that consider the specific environmental contexts of development sites and can mitigate the absence of efficacy in current mitigation approaches [18,19].

In this study, we employed the Biodiversity Tipping Point framework to evaluate the effectiveness of mitigation plans. This framework allows for a precise understanding and prediction of the non-linear changes in ecological responses due to urbanization, and it classifies the extent of impact changes before and after development based on tipping points [20]. Notably, the framework enables the analysis of how sensitively ecological responses react to mitigation measures, using 'tipping points' as a benchmark. However, previous studies have primarily remained theoretical, focusing on ecological resilience and lacking substantial analysis based on actual data. This approach facilitates a detailed analysis of how mitigation plans in environmental impact assessments vary according to environmental factors and how they differ among species.

Therefore, this study utilized the Biodiversity Tipping Point (BD-TP) framework to analyze data from EIA reports, examining the actual effectiveness of mitigation plans. It assessed how these plans vary in effectiveness according to the surrounding environment and across different species. Drawing on 288 EIA reports from development projects in Korea, this review evaluated the effectiveness of post-implementation mitigation measures based on the disturbance level and surrounding environment. The projects were carefully selected to include only those that implemented all 10 mitigation measures classified according to the Wildlife Conservation Comprehensive Plan [21]. Using the biodiversity tipping point (BD-TP) framework proposed by Ref. [20], we categorized the effects of mitigation measures on biodiversity into four levels (very high, high, low, and very low) and analyzed their effectiveness.

2. Methods

2.1. Study area

Korea is located on the Korean Peninsula in East Asia and has retained approximately 70 % of its natural habitats (Fig. 1 (A)). The eastern region is characterized by high altitudes owing to the Taebaek Mountains, whereas the western region is characterized by low-elevation plains and cultivated lands. The country has a continental climate with distinct seasonal variations, including cold and dry winters and hot and humid summers. Since the late 1990s, rapid urbanization has led to a continual decline in natural habitats in the country [22]. By the end of 2016, 2,449 damaged habitats were identified within the core ecological axes of the Korean Peninsula, including Baekdudaegan and Jeongmaek [23]. This has significantly impacted Korea's biodiversity, with certain species experiencing population declines, such as the White-tailed Eagle and Greater Horseshoe Bat, and moving from near-threatened status to vulnerable on the Red List by the International Union for Conservation of Nature [24].

Although habitat protection in Korea was low until the early 2000s, habitat conservation policies implemented post-2000 have led to a steady increase in protected areas. As of 2023, Korea has approximately 1,800 designated habitat protection areas, including natural reserves, protected areas, and ecosystem conservation areas, which cover approximately 2.6 million ha [25]. Despite these efforts, biodiversity loss is continuously increasing, and thus, a comprehensive examination of the impact of development projects on biodiversity is required.

We specifically examined the influence of development projects, classified as area-based and line projects, on biodiversity changes exclusively in the Republic of Korea (Fig. 1 (B)). Area-based projects type was categorized into four types, namely, urban planning facilities, residential construction, land development, and innovative city development, while line projects type was divided into three types, namely, new road construction, road extension, and urban and non-urban road construction. Data on the location, scale, and duration of these projects were collected and analyzed.

2.2. Data collection

Variations in terrestrial biodiversity were investigated as reported in EIA and post-EIA reports. Post-EIA reports aim to verify the alignment between predicted impacts and actual environmental effects during the project duration. To this end, monitoring and impact assessments are conducted annually for a period of three to five years following project completion. In compliance with the Korean Environmental Impact Assessment Law, we focused on projects that were monitored from the start of the project to three years post-completion and completed between 2004 and 2013. We reviewed the biodiversity monitoring and reported mitigation measures data included in the EIA. Ultimately, a total of 288 projects, both area-based and line projects, were considered in our analysis.

Data from the selected development projects were extracted from the flora, fauna, and natural environmental assets sections of the corresponding EIA reports. The data were then systematically organized into four distinct categories: extent of disturbance, surrounding environment, mitigation plan implementation, and biodiversity. The extent of disturbance was evaluated based on the development area, period, and project type. Surrounding environment data were collected by considering the distance to protected areas, urban areas, and green areas and utilizing ecological nature map and digital elevation model (DEM) data [26]. Biodiversity was assessed based on the species richness of the examined data.

To minimize overestimating biodiversity, we excluded data acquired through literature reviews in the EIA reports and focused solely on the actual monitored species. This ensured a more accurate representation of biodiversity and provided a robust foundation for analyzing the impact of various factors on biodiversity.

2.3. Control variables: mitigation measures

To examine the influence of the extent of disturbance and surrounding environment on biodiversity following mitigation plan

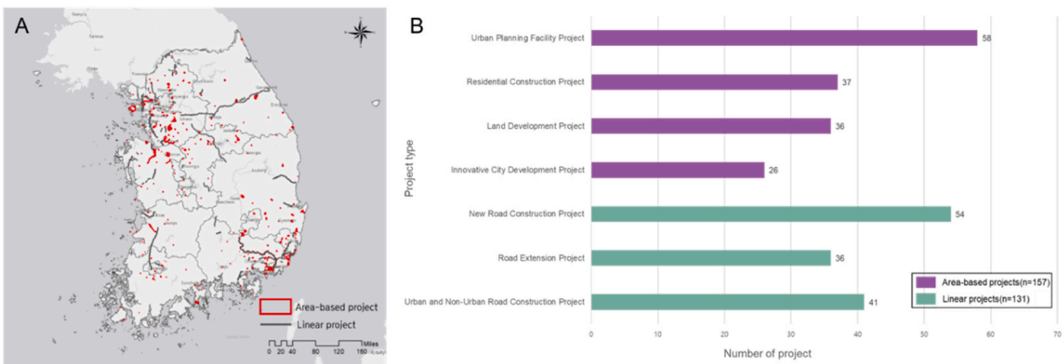

Fig. 1. (A) Study area (Korea, Republic of), (B) Location and types of the 288 projects considered for assessment in the present study.

Table 1
Examples of the completed fields in the database for 10 out of 288 projects.

Project code	Environmental factors						Disturbance level			Effect type (Very low = 1, Very high = 4)			
Code	Dis_proarea	Dis_urban	Dis_green	Eco_map	DEM	Species richness	Area	Period	Type	Mammal	Bird	Amphibian	Reptile
DG1997K002	103.7911	28.06435	0.812174	1.066751	167.7419	14	3627765	3	Urban Planning Facility Project	D	B	C	D
DG2002Q004	79.56833	3.930556	1.416667	1.657895	243.6567	8	278802	9	Urban Planning Facility Project	C	C	A	A
DG2005Q005	222.4693	12.05405	0.918919	2	490.4008	1	130056	8	Residential Construction Project	B	D	B	B
DG2006Q002	30.72	4.113636	3.113636	1.824859	383.4305	2	160018	1	Residential Construction Project	B	C	B	B
DG2006Q006	65.83412	11.10638	1.553191	2.121693	136.1149	14	313131	2	Residential Construction Project	C	D	C	C

DEM, digital elevation model.

implementation, we conducted a comprehensive investigation into the types of mitigation measures implemented across 288 projects. Our analysis revealed that while the objectives within the project reports were consistent, the terminology used to describe the mitigation plans varied significantly. For example, phrases such as "Reduction of noise and vibration sources," "suppression of unnecessary noise," and "minimization of noise and vibration" were consolidated under the category "Noise and Vibration." To ensure consistency across diverse mitigation plans, we referred to the Comprehensive Plan for Endangered Wildlife Conservation [21,27], which categorizes mitigation strategies into three major categories and ten subcategories as follows: habitat environment creation (including habitat creation, conservation, and green networks), management of environmental threat factors (including particulate matter removal, pollutant emission minimization, noise and vibration minimization, and light pollution reduction), and accident prevention measures (including wildlife protection education, ecological construction management, and roadkill prevention).

To comprehensively examine biodiversity and changes in biodiversity following mitigation plan implementation, we selected 288 projects that fully implemented all 10 mitigation strategies, as specified in the post-EIA. Additionally, information regarding the implementation of the 10 mitigation measures for each project was extracted from Environmental Impact Assessment reports and post-environmental impact documents, as well as from photographs included. Table 1 showed examples of data collected for 10 of the 288 projects, as reviewed from the Environmental Impact Assessment Information System (https://www.eiass.go.kr and http://data.go.kr).

2.4. Biodiversity trend analysis for effect classification

EIA and post-EIA documents are mandatory for development projects, which are monitored annually [28]. Monitoring commences at the start of construction and continues through the post-construction phase, with a distinction made between the construction and operational phases based on pre- and post-completion timelines [7]. In this study, we utilized species monitoring data collected during three to five sessions conducted annually. Presence-absence data (1,0) were collected for mammals, amphibians, and reptiles, whereas both presence-absence data and individual counts were recorded for birds.

EIAs use the annual species richness (SR) biodiversity index to discern biodiversity trends based on the collected data. This index, which is evaluated based on species occurrence, is a simple and intuitive measure among various biodiversity indices and can be used to compare biodiversity across different regions and timeframes. Herein, biodiversity indices were evaluated using SR, as employed in the EIA. Species occurrence was evaluated for mammals, amphibians, and reptiles, whereas the Margalef richness index calculated according to Equation (1) was used for birds, the individual counts of which were monitored.

$$\mathrm{RI} = \frac{S-1}{\ln N} \tag{1}$$

where S is the total number of species and N is the total density of species. Time-series data collected through monitoring assist in analyzing biodiversity trends in relation to the extent of disturbance and mitigation plan implementation [29]. However, biodiversity does not exhibit simple linear changes, and the effects of disturbances may manifest slowly over time, thereby limiting traditional pre- and post-intervention mean differences and trend change pattern analyses [30]. In this study, we applied the Biodiversity Tipping Point (BD-TP) framework, as introduced by Ref. [20], to dynamically assess the impacts of development projects on biodiversity. This innovative framework is designed to evaluate structural, compositional, and functional changes in ecosystems that result from habitat loss due to disturbances, while also integrating the interactions between ecological and social systems [20]. Additionally, its ability can capture the non-linear changes in biodiversity that are often overlooked by conventional pre- and post-intervention analyses. The BD-TP framework facilitates a dynamic, extended temporal evaluation of biodiversity changes, which is essential for quantifying the effectiveness of mitigation measures in reducing the risk of reaching biodiversity tipping points. This approach allows for a more comprehensive understanding of how disturbances impact biodiversity over time, offering crucial insights for effective conservation strategies. Moreover, it quantifies natural losses owing to disturbances, identifies when biodiversity tipping points occur, and provides

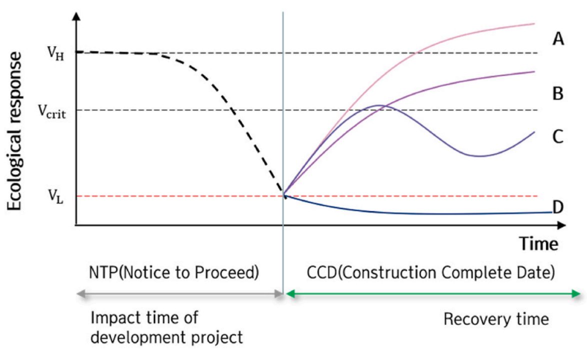

Fig. 2. Species richness variation graph using the framework of the risk of biodiversity tipping points (BD-TPs). A~D indicated Categorization of Ecological Response Effects Post-Mitigation Plan Implementation. The effects are divided into four levels, with 'A' representing the highest level of effectiveness and 'D' the lowest.

information for policy decisions and planning [31]. It also evaluates how disturbance levels escalate the risk of reaching tipping points, and how mitigation plans effectively reduce this risk [32].

To apply the BD-TP framework effectively, we conducted seasonal biodiversity monitoring annually, collecting both presence-absence data and individual counts across different taxa. We defined the amounts of biodiversity change as effect types based on the BD-TP conceptual theory, categorizing post-completion effects into four distinct levels relative to pre-development biodiversity indices. This methodology allowed us to analyze the efficacy of mitigation plans under various levels of disturbance and environmental conditions for different species groups. Given the challenges in quantitatively evaluating the effects of mitigation plans on biodiversity using time-series data, this study defined biodiversity change amounts as effect types based on the conceptual theory of BD-TP (Fig. 2). In the pre-development phase, the highest value of the biodiversity abundance index was defined as V_H, the point where the abundance index drastically decreased because of disturbance was defined as V_crit, and the lowest value was defined as V_L. Post-completion, the effect types were classified as A (very high) if higher than V_H, B (high) if lower than V_H but higher than V_crit, C (low) if lower than V_crit but higher than V_L, and D (very low) if lower than V_L. We evaluated how and to what extent the effects of the mitigation plans on biodiversity, classified into four types, were influenced by the extent of disturbance and surrounding environment for different species (mammals, birds, amphibians, and reptiles).

2.5. Statistical analysis

This study examined the impact of disturbance magnitude and surrounding environmental variables on the effectiveness of mitigation measures. The effectiveness was assessed by comparing species richness before and after development, with performance categorized into four degrees based on the Biodiversity Tipping Point (BD-TP) framework. The extent of disturbance was defined by project scale and duration, while environmental variables were identified from the EIA under the natural environmental assets section, including distance from protected areas, distance from urban centers, DEM ecological naturalness, and pre-development abundance indices. Mitigation plan effectiveness was categorized into "very low," "low," "high," and "very high."

The difference in mitigation plan effectiveness based on the extent of disturbance was analyzed using analysis of variance. Subsequently, to discern the differential effectiveness of mitigation plans across project types (area-based projects and line projects) in varying environmental contexts, the Kruskal–Wallis test was employed, as the data were not normally distributed (Shapiro-Wilk test: $p < 0.05$). Subsequently, the Mann–Whitney pairwise comparison with Bonferroni correction was applied to the raw data to further test the differences.

Redundancy analysis (RDA) ordination was performed to understand the relationships among species-specific effects driven by the extent of disturbance, environmental variables, and mitigation plans. The relationship correlations between environmental factors and the extent of disturbance with species-specific mitigation effectiveness was identified through a vector-based analysis performed using the "envfit" function of the vegan package in R programming language. Statistical significance was validated through 999 random permutation tests. All statistical analyses were performed using R version 3.1.3 [33].

3. Results

3.1. Classification of biodiversity trends

The effects of the mitigation plan on biodiversity were examined using the BD-TP framework by classifying changes in biodiversity before and after project completion into four distinct types (Fig. 3). The 288 selected projects were comprehensively analyzed and

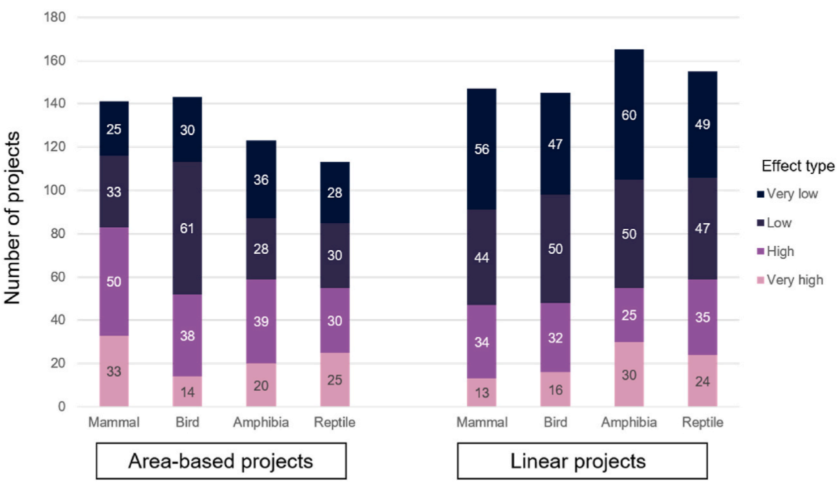

Fig. 3. Number of projects including effect type by project type and species.

segregated by project type and species. The results revealed significant variations in the effectiveness of the mitigation plans across different project types and species. The classification yielded a relatively small number of projects with "very high" effectiveness ratings, suggesting a substantial need for improvement in current mitigation strategies. The variation in effectiveness was further elucidated when the projects were analyzed based on their typology (area-based and linear projects). In area-based projects, the number of projects with a "high" effectiveness rating was significantly higher for mammals, amphibians, and reptiles while the number with a "low" effectiveness rating was predominantly observed for birds.

Linear projects demonstrated contrasting trends. Most projects involving mammals, amphibians, and reptiles were rated as "very low" in effectiveness. This stark contrast between area-based and linear projects highlighted the different effects of project typology on biodiversity. Notably, amphibians and reptiles appeared to be more adversely affected by linear projects than area-based projects, as evidenced by the high number of projects with a "very low" effectiveness rating. Furthermore, a comparative analysis of area-based and linear projects revealed divergent trends in effectiveness ratings. While "high" effectiveness ratings predominated in area-based projects, "very low" ratings were more common in linear projects.

3.2. Analysis of the differences in the effect of mitigation measures according to the disturbance level

We investigated the variance in the effect types of mitigation plans after project implementation according to the disturbance level. Boxplots revealed a discernible trend across species, with the effect of mitigation plans decreasing with increasing project area and length (Fig. 4). Among the linear projects, "very high" and "low" effect types differed significantly with increasing project length for all species, suggesting that mitigation plan effectiveness may decline with extended project length, despite the similarity among mitigation plans being implemented. Conversely, in areal projects, project area and effect type differed significantly among mammals, amphibians, and reptiles but not among birds. Notably, the boxplot for birds exhibited negligible differences across all effect types and project areas, with the greatest effect achieved when the project area was large.

Analysis of the effect type in relation to the project period for different project types revealed significant differences between "very high" and "very low" effect types for amphibians and reptiles in areal projects. Additionally, a significant difference between "very high" and "high" effect types was observed for birds, while other effect types were unaffected by the project period. Notably, mammals showed variations in effect with the project area, although no significant results were found during the project period. Contrastingly, all species in linear projects demonstrated significant differences between "very high" and "very low" effect types. Analysis of variance

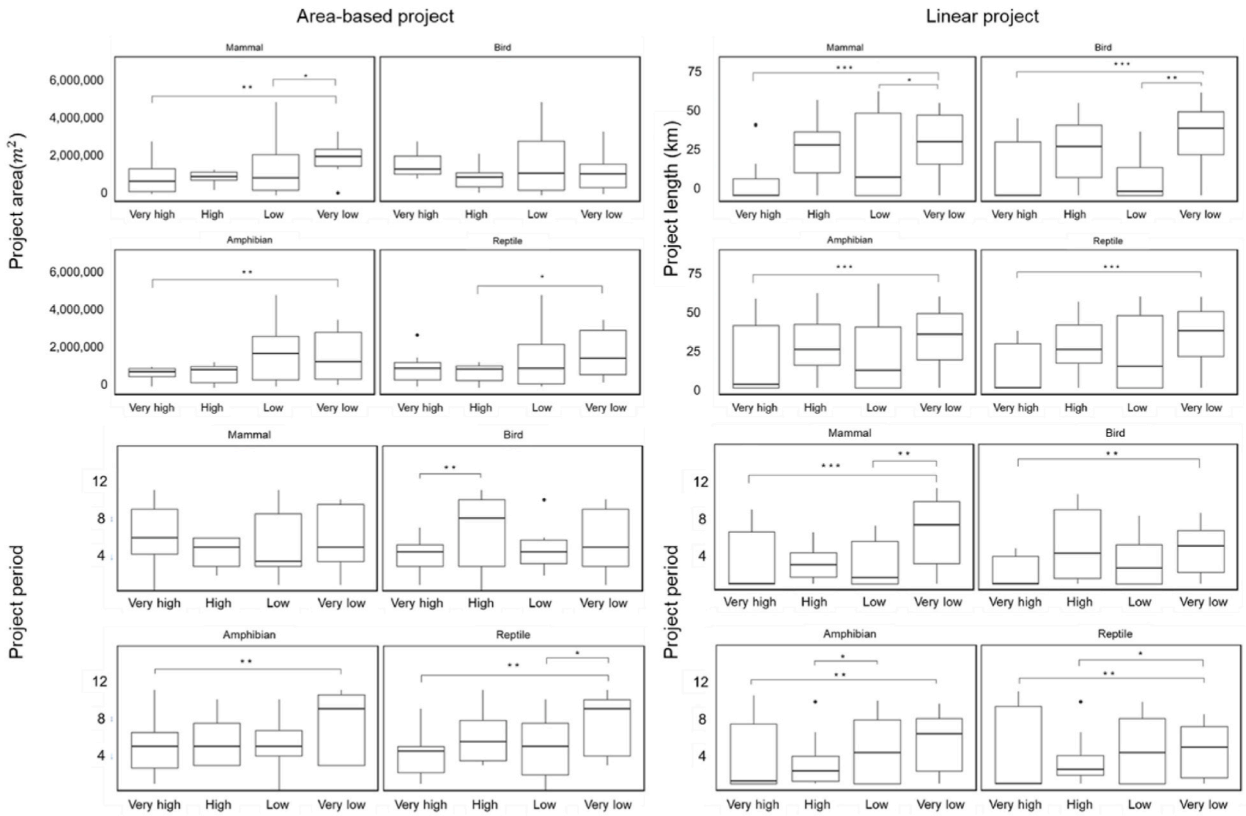

Fig. 4. Boxplots showing project area, length, and period for species richness effect type (median, interquartile range, maximum and minimum values). A significant difference was observed between the effect type. * indicates $p \leq 0.05$, ** indicates $p \leq 0.01$, and *** indicates $p \leq 0.001$.

and boxplots revealed that linear projects were more sensitive to the disturbance level than areal projects. Specifically, in areal projects, the impact varied significantly among species depending on the disturbance type (Table 2). The analysis revealed that the degree of species richness decline varies according to the type of development project and the species involved. Notably, birds exhibited the most significant reductions in species richness across all types of projects. Furthermore, linear projects such as road construction and road extension projects were found to have a particularly large impact on species richness decline.

3.3. Analysis of differences in biodiversity effect on environment variables

The Kruskal–Wallis analysis revealed that the relationship between environmental variables and mitigation plan effect type varied across species groups (Table 3). Table 3 presented the statistical analysis results of the effectiveness of mitigation measures, examining whether performance differences occur based on species type, development type, and surrounding environmental factors. For area projects, distance to protected areas and mitigation plan effectiveness were significant for all species groups, while DEM data were not significant. Notably, mammals showed significant differences in four environmental variables, excluding DEM, whereas reptiles showed significant differences in the distance to protected areas and urban areas. Conversely, for linear projects, all species groups showed significant differences in distance to urban areas while no significant differences were observed in the ecological nature map.

After applying the Bonferroni correction, pairwise Mann–Whitney comparisons revealed that the surrounding environment generally had a significant effect on the effectiveness of the mitigation plans. For example, projects closer to protected areas, farther from urban areas, and with higher pre-development biodiversity had more effective mitigation plans. Reptiles in areal projects exhibited a higher effect type as the distance to urban areas increased, with "very low" (effect type = 1) and "low" (effect type = 2) effect types observed with decreasing distance. However, the DEM produced different results for amphibians and reptiles and the ecological nature map produced different results for birds.

3.4. Redundancy analysis

RDA was performed to examine the relationships between six environmental variables (ecological nature map, DEM, distance to protected area, green area, urban area, and biodiversity before development), two disturbance variables (development period and development area), and the effects on four species groups (mammals, birds, amphibians, and reptiles) contingent on mitigation plan implementation (Fig. 5). Seven of the eight variables explained a substantial amount of variance. The ranks of the variables in terms of explanatory power were as follows: development area (16.8 %), development period (13.2 %), distance to protected area (11.2 %), distance to green area (8.6 %), distance to urban area (7.9 %), biodiversity (6.5 %), and DEM (4.8 %). All six variables remained significant after partial RDA with 1–6 covariates.

The canonical axes explained 26.4 % of the total variance in the effect-type data. Although Axes 1 and 2 were constrained, Axis 2 was marginally significant (F-ratio = 6.74, $p = 0.053$) (Table 4). Axis 1 indicated the primary environmental influences on biodiversity, emphasizing the effects of development timelines and proximity to green areas on species variability. Axis 2 showed the spatial environmental factors, such as elevation and urban proximity, and their significant impacts on species distributions. Axes 3 and 4 investigated subtler and complex environmental interactions, which contribute to understanding variations in ecological responses, though less significantly than the first two axes. The eigenvalue of Axis 1 was 1.7 times greater than that of Axis 2. Development period, distance to green areas, and biodiversity were significantly correlated with Axis 1, whereas DEM, distance to protected areas, and distance to urban areas were significantly correlated with Axis 2. Distance to protected areas, green areas, and biodiversity exhibited positive intra-set correlations, whereas the remaining environmental variables demonstrated negative correlations. The intra-set correlations spanned from −0.26 to 0.42.

The RDA-derived triplot, which depicts the interrelationships among disturbance levels, surrounding environmental variables, and species-specific effect types according to the mitigation plan, illustrated associations based on vector orientations. Projects closer to protected areas and green spaces were generally in the first quadrant, whereas projects with longer development periods, larger areas, and proximity to urban areas were in the fourth quadrant. The RDA species scores illustrated the direction of increasing SR and its association with environmental variables, with each species group represented in different quadrants. All species groups were predominantly abundant in the right quadrants, exhibiting negative relationships with disturbance variables (development area, period, and distance to urban area). Mammals demonstrated an increased effect type with closer proximity to protected areas and green

Table 2
Variation in species richness decline by project type and species group.

project	mammal		bird		amphibian		reptile	
	mean	sd	mean	sd	mean	sd	mean	sd
Innovative City Development Project	3.07	2.76	5.85	3.21	3.46	2.68	3.48	2.89
Land Development Project	2.56	2.55	5.11	2.89	3.15	2.20	3.30	2.45
New Road Construction Project	3.29	2.98	6.71	2.87	3.67	3.18	3.69	2.87
Residential Construction Project	2.75	2.44	6.33	2.89	3.12	2.95	3.33	2.72
Road Extension Project	2.57	2.74	6.93	2.13	4.29	3.24	4.21	2.94
Urban Planning Facility Project	3.68	2.80	6.38	2.71	3.93	2.83	4.11	3.11
Urban and Non-Urban Road Construction Project	3.21	3.36	3.93	3.10	2.86	1.75	3.29	1.94

Table 3
Kruskal–Wallis analysis results for environmental drivers, followed by post-hoc pairwise Mann–Whitney comparisons applied with a Bonferroni correction.

Environmental drivers	Group	Kruskal–Wallis		Mann–Whitney	
		Area project	Line project	Area project	Line project
Distance of protected area	Mammal	0.015	0.113	4>1, 2	-
	Bird	0.047	0.065	4>1, 3	-
	Amphibian	<0.001	0.002	4>2	4>2
	Reptile	0.002	<0.001	4>2	4>2, 3
Distance of urban area	Mammal	<0.001	0.002	4>1	4>1
	Bird	0.256	0.001	-	4>1, 2
	Amphibian	0.002	0.03	4.3>1, 2	4>1, 2
	Reptile	0.001	0.004	4>1, 2	4>1
DEM	Mammal	0.098	0.125	-	-
	Bird	0.156	0.254	-	-
	Amphibian	0.134	0.041	-	1>4
	Reptile	0.265	0.004	-	1>3, 4
Ecological zoning map	Mammal	0.341	0.452	-	-
	Bird	0.03	0.245	1>3	-
	Amphibian	0.541	0.423	-	-
	Reptile	0.211	0.152	-	-
Biodiversity before development	Mammal	<0.001	0.002	4>1	4>1, 2
	Bird	0.04	0.012	4>2	1>3
	Amphibian	0.002	0.152	4>2	-
	Reptile	0.132	0.263	-	-

DEM, digital elevation model.
Gray shading indicates nonsignificant results. 1: "Very low," 2: "low," 3: "high," and 4: "very high."

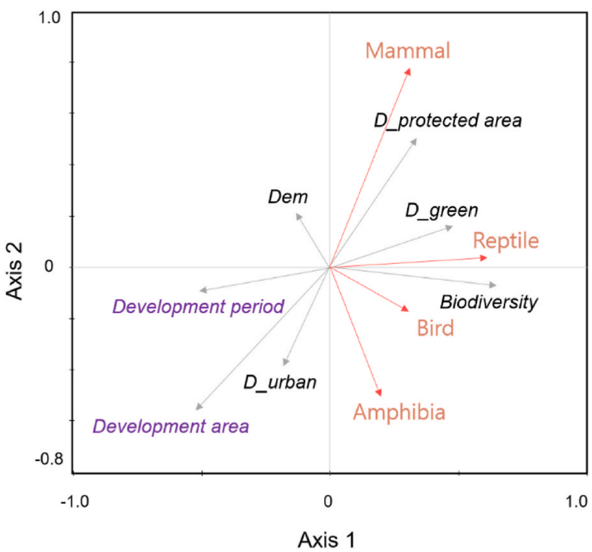

Fig. 5. Redundancy analysis (RDA) showing the sample scores plotted relative to the significant environmental variables.

Table 4
RDA summary, including canonical coefficients, their respective t-values, and intra-set correlations of environmental variables with the axes. Axes represent dominant and nuanced environmental gradients that influence species responses to disturbances and mitigation efforts.

	Axis 1	Axis 2	Axis 3	Axis 4
Eigen value	8.2122	4.7488	3.8525	2.79874
Cumulative %	16.6 %	24.4 %	26.2 %	26.4 %
Significance test of axis F-ratio	8.96	6.74*	1.24	
Canonical coefficients				
Distance to protected area	0.42	0.38	0.28	−0.12
Distance to green area	0.34	−0.12	−0.22	0.33
Distance to urban area	−0.52	−0.34	0.12	−0.21
DEM	−0.24	0.11	0.33	0.15
Development area	−0.47	−0.41	−0.32	−0.34
Development period	−0.38	−0.34	−0.42	−0.22
Biodiversity	0.32	0.28	−0.32	0.25
Canonical coefficients				
Distance to protected area	2.41	1.38	2.63	−1.16
Distance to green area	2.25	−1.15	−1.52	2.22
Distance to urban area	−3.14	−3.11	1.63	−1.16
DEM	−2.21	1.13	2.86	1.14
Development area	−2.51	−1.75	−2.43	−1.26
Development period	−2.33	−1.66	−2.86	−1.16
Biodiversity	2.85	0.94	−2.29	1.14
Intra-set correlations				
Distance to protected area	0.32	0.33	0.21	−0.12
Distance to green area	0.31	0.21	−0.12	0.33
Distance to urban area	−0.26	−0.18	0.15	−0.25
DEM	−0.23	0.26	−0.22	−0.35
Development area	−0.42	−0.37	0.33	−0.25
Development period	−0.31	−0.29	0.24	−0.42
Biodiversity	0.32	−0.31	0.12	0.24

DEM, digital elevation model; RDA, redundancy analysis.

spaces, and farther distances from development areas, periods, and urban areas. Reptiles and birds exhibited a significant positive relationship with biodiversity, whereas amphibians showed a negative relationship with the DEM and a significant negative relationship with distance from urban areas.

4. Discussion

4.1. Fluctuations in biodiversity index according to the development project

The close association between urban development projects and biodiversity is a key focus of environmental management research. This study examined the variations in the effectiveness of mitigation plans, which highlight the need for tailored strategies that consider both project and environmental characteristics. The findings confirmed that the degree of disturbance, as summarized by the scale and duration of development projects, significantly affected biodiversity indices. Differences were observed in mitigation plan effectiveness according to the disturbance level, thereby underscoring the nuanced interplay between development projects and biodiversity [34] and suggesting that the potential impact gradient can be moderated using well-organized mitigation plans. Large-scale and long-duration projects tend to have more pronounced adverse impacts on biodiversity and thus necessitate more robust and tailored mitigation strategies [35]. Moreover, the study revealed that similar mitigation plans can yield disparate outcomes depending on the surrounding environment, thereby highlighting the importance of contextual factors in mitigation plan design and implementation.

Previous studies have reported a positive correlation between biodiversity and proximity to protected areas and green spaces and a negative correlation between biodiversity and the degree of disturbance [36–38]. However, the relationship between development duration, SR, and ecosystem post-development stabilization remains relatively understudied. Although the impact of disturbances on biodiversity is well-recognized, the diverse attributes and characteristics of disturbances need to be investigated to understand their nuanced effects on biodiversity [39].

Habitat segregation at high and low altitudes can restrict the movement of highly mobile avian species, leading to species differentiation and population decline [40–42]. Conversely, mammals may experience population increases owing to reduced competition in isolated regions [43,44]. Using high DEMs, populations of amphibians and reptiles, which traverse both aquatic and terrestrial habitats, have been reported to decline in complex terrains [45]. However, reptiles, which have a lower water dependence and higher mobility than amphibians, may survive by moving to other habitats in restricted areas [46]. These insights from previous studies provide robust support for our findings.

Previous studies and the current study provide nuanced insights into the multifaceted impacts of development projects on biodiversity and highlight the need for a more comprehensive examination of this complex issue. A deeper understanding of how diverse attributes of disturbances, coupled with species- and habitat-specific characteristics, influence biodiversity is required. This calls for a more holistic approach to EIAs and mitigation plan formulation that can adequately address the diverse needs and vulnerabilities of different species and ecosystems, and significantly enhance the effectiveness of mitigation measures and contribute to sustainable urban development.

4.2. Underestimation of biodiversity decline due to inadequate monitoring

The adverse effects of development projects on biodiversity are well-documented; however, the extent of these effects can be significantly underestimated owing to inadequate monitoring practices. Our analysis revealed that the scale and duration of development projects negatively affect most species [47]. However, notable exceptions were observed for mammals in relation to development area, and for birds in relation to project duration, but the results were not significant. This discrepancy could be attributed to various factors, including inadequate monitoring. Specifically, despite the large scale and extended duration of projects, such as "Everland Amusement Park Construction Project," "International Industrial Logistics City Behind Busan New Port," and "Seoul-Wonju Expressway Private Investment Project," a tendency towards increased biodiversity indices was observed. This unexpected trend highlights the potential pitfalls of the current monitoring practices, which may fail to capture the true extent of biodiversity decline. Monitoring guidelines in South Korea recommend that biodiversity should be monitored 4–5 times annually, aligning with the country's four-season climatic characteristics [18]. However, critical aspects, such as the selection of monitoring sites and timing of monitoring sessions, are often decided by investigators, and these decisions can be subjective and thus may vary between projects. This lack of standardization could lead to inconsistent data collection and potential underestimates of the adverse effects on biodiversity.

The subjective nature of current biodiversity monitoring practices highlights the urgent need for more objective, standardized, and robust monitoring frameworks. Recent technological advances provide promising avenues for addressing this gap. For example, the development of image recognition models powered by Artificial Intelligence for wildlife classification heralds a new era of enhanced monitoring capabilities [48–50] that could significantly augment the accuracy and comprehensiveness of biodiversity monitoring. This could enable a more precise understanding of the impacts of development projects. However, the adoption and integration of such technologies into EIAs require supportive policies and institutional frameworks. Furthermore, post-EIA reports that conduct annual monitoring after project development should systematically implement the timing, location, and methods of investigation to enhance the effectiveness of the Environmental Impact Assessment. Establishing conducive policies and frameworks that facilitate the utilization of advanced monitoring technologies can significantly enhance the accuracy of EIAs and contribute to more informed decision-making and effective mitigation strategies.

In conclusion, robust biodiversity monitoring practices play a critical role in accurately assessing the impact of development projects; thus, advanced monitoring technologies should be adopted, and supportive policy frameworks should be established to increase the precision and reliability of biodiversity impact assessments. Through these advancements, a more accurate understanding of the impacts of development projects on biodiversity can be attained, thereby facilitating more effective conservation and mitigation efforts.

4.3. Evaluating the effectiveness of mitigation measures

Mitigation measures are crucial tools for alleviating decreases in biodiversity and promoting research aimed at resolving the effectiveness issues of actual plans through qualitative and quantitative evaluations. Qualitative evaluations have primarily been conducted using methods such as the Leopold matrix, checklist method, and EIA literature reviews to elucidate the causes of effectiveness issues [51–53]. Recent advancements in quantitative research have shifted towards leveraging time-series data to understand the impacts of urbanization, natural disasters, and other disturbances on biodiversity or evaluate the effects of policy changes and technological interventions. Among these, methodologies such as before-after-control-impact analysis, trend analysis, biodiversity resilience function, and comparisons of mean differences before and after interventions have been extensively utilized in ecology to assess the impact of interventions [12,54,55]. However, these methodologies require experimental setups to understand what would have transpired in the absence of interventions, and thus, limit analysis of data collected from EIAs.

Using these methodologies, previous research has highlighted the potential of mitigation measures to alleviate biodiversity decline issues, albeit with suboptimal performance. The low implementation rates of cost-intensive mitigation measures, such as ecological corridors and alternative habitats, have further exacerbated the effectiveness of the mitigation plans. This study examined the effectiveness of mitigation plans by using the mitigation plan as the control variable and focusing on projects that fully implemented all 10 mitigation plans based on the classification system used in previous research. Nevertheless, the effectiveness can vary even among identical mitigation plans depending on the scale, location, and characteristics of the mitigation measures [56,60]. Despite these limitations, the analysis of the causes of the differences in effectiveness through the application of mitigation measures provides significant insights that support the finding of previous research.

4.4. Using genetic and functional biodiversity indices

Biodiversity was evaluated using the SR index, which is commonly used for EIA. However, this index, which is based on species presence or absence, does not consider the interactions among different species and between different ecosystem types [57,58]. For example, the index may remain constant over time even when the actual species changes. Urban development may lead to a decline in native species; however, the SR index may remain unchanged due to an increase in disturbance-adapted species [59,60]. Similarly, a balanced predator-prey distribution may maintain the SR index; however, a disturbance that favors predators could alter ecosystem dynamics without changing the index [61]. To address these issues, analysis across species and ecosystems using various genetic and functional diversity indices is imperative [62]. Exploring genetic and functional diversity can provide insights of biodiversity that are otherwise not captured by the SR index, thereby providing a more nuanced understanding of ecosystem dynamics [63]. For example, genetic diversity indicates the potential resilience of an ecosystem to disturbances, whereas functional diversity can elucidate the functional roles and interactions of species within an ecosystem [54]. These biodiversity dimensions can provide invaluable insights into the actual impacts of development projects, which may be underestimated or overestimated by the SR index alone. The use of these diverse indices can significantly enhance the accuracy of EIAs, thereby contributing to more effective and informed mitigation plans.

To effectively use biodiversity indices, factors, such as efficient monitoring guidelines, should be considered. The reliability and comprehensiveness of biodiversity assessments in development projects can be improved by considering the following.

(1) Consistency and continuity in monitoring: Maintaining consistency and continuity in selecting survey sites, timing, and methods is crucial during the construction and operational phases of a project. This helps to mitigate the shortcomings of monitoring and improves the reliability of the data collected. Inconsistent monitoring practices can lead to biased or incomplete data, resulting in inaccurate biodiversity assessments. Therefore, well-organized monitoring guidelines that ensure methodological consistency are essential for accurately evaluating biodiversity impacts.
(2) Adaptive post-EIAs: Environmental conditions are dynamic and subject to change due to various factors, including developmental activities. Therefore, adaptive post-EIAs are essential to accurately reflect these changes. To effectively monitor the predicted impacts of development projects and the efficacy of mitigation plans, it is crucial to employ advanced monitoring techniques such as camera trapping with systematic monitoring system. This approach not only facilitates real-time data collection but also has the potential to contribute to an international database that could serve as foundational data for achieving global biodiversity targets. Integrating such technologies ensures that adaptive post-EIAs can provide a more accurate assessment of biodiversity status and the impacts of development projects, supporting the broader objectives of global environmental stewardship.
(3) Extended monitoring period: Evaluating the impacts of development projects and the effectiveness of mitigation plans requires a long-term perspective. Extending the monitoring period from 3 to 10 years in post-EIAs facilitates a more comprehensive understanding of the mid- to long-term effects. This extended timeframe provides a more holistic view of developmental impacts on biodiversity, enabling a better evaluation of the effectiveness of the implemented mitigation measures [64].

A methodologically consistent, adaptive, and long-term monitoring approach is instrumental for understanding the impacts of development on biodiversity and evaluating the effectiveness of mitigation measures. Such an approach is fundamental for informed decision-making and effective biodiversity conservation in urban development and environmental management.

The current study presented certain limitations. For example, the biodiversity index and environmental variables used to consider the effects on mitigation measures were obtained from EIA reports. However, to improve the effectiveness of EIAs, more advanced spatial data should be used, such as functional diversity, anthropogenic environmental variables, and vegetation data. Integrating this additional information would allow for more effective assessments of biodiversity loss and help minimize the impact of urban development on species.

5. Conclusion

The multifaceted investigation conducted in this study highlights the intricate dynamics among development projects, mitigation measures, and biodiversity, thereby highlighting the need for a nuanced, tailored approach to environmental management amid urban development. The findings underscore the significant variations in the effectiveness of mitigation plans based on the disturbance level and surrounding environmental context and call for a more refined spatial-specific strategy to devise and execute mitigation measures.

The analysis revealed that the surrounding environmental variables significantly influence the effectiveness of the mitigation plans. Proximity to protected areas, existing green spaces, and high-biodiversity regions can significantly enhance the performance of mitigation plans. Additionally, the impact on various species varies with the surrounding environmental factors; thus, an integrated mitigation plan that considers the differential impacts on different species is necessary to reduce biodiversity decline.

We used the BD-TP framework to comprehensively categorize biodiversity trends pre- and post-construction, and it revealed the differential impacts across various species and project types. Furthermore, the application of time-series data analysis, as exemplified by the BD-TP framework in this study, underscores the value of leveraging long-term ecological data to discern the dynamic effects of urban development on biodiversity. This approach facilitates a more nuanced understanding of how biodiversity responds over time to development and mitigation efforts, highlighting the necessity for continuous, adaptive monitoring strategies. Advancements in monitoring technologies, bolstered by supportive policy frameworks, can significantly augment the accuracy and comprehensiveness of biodiversity assessments, thereby fostering more effective mitigation strategies. Moreover, this study elucidated the potential limitations of employing a singular biodiversity index and indicated the need for a more holistic approach that can include genetic and functional diversity indices. This broader perspective could reveal the nuanced impacts of development projects, which may be obscured by a sole reliance on SR indices. The findings suggest an extended monitoring period in post-EIAs to capture mid- to long-term impacts and the effectiveness of mitigation measures, thereby providing a more accurate reflection of biodiversity dynamics in the context of urban development.

Overall, this study advocates for a paradigm shift in environmental management practices towards a more nuanced, adaptive, and region-specific approach to devising, implementing, and evaluating mitigation plans. Underpinned by robust monitoring frameworks and a broader understanding of biodiversity, this approach can significantly enhance the effectiveness of conservation efforts, thereby contributing to a more sustainable interplay between urban development and environmental preservation.

Our analysis provides a broader understanding of the effectiveness of mitigation measures for preserving biodiversity amidst ongoing developmental projects. The findings provide a robust foundation for future research aimed at refining mitigation strategies and monitoring frameworks and foster a more informed, effective, and sustainable approach to environmental management amidst ongoing urban development.

Data availability statement

The data will be available on request.

CRediT authorship contribution statement

Eun Sub Kim: Writing – original draft, Methodology, Formal analysis, Data curation. **Dong Kun Lee:** Writing – review & editing, Conceptualization. **Jiyoung Choi:** Writing – review & editing, Visualization, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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