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Aims and Scope

Proceedings of the National Institute of Ecology of the Republic of Korea (PNIE) is an open access and online journal aimed at promoting outcomes of basic ecological researches carried out in Korea and abroad. The journal focuses on not only basic ecological research on terrestrial and aquatic populations, communities, ecosystems and landscapes but also applied issues such as data science and climate change based on ecological research.

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Review Article

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Urban Nature Indexes: Methodology and Strategic Directions in Korea

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ABSTRACT

Cities are simultaneously vulnerable ecosystems exposed to risks such as heatwaves, floods, and air pollution, while also holding potential to drive biodiversity conservation and resilience. As cities play an increasingly critical role in achieving global biodiversity targets, the International Union for Conservation of Nature developed the Urban Nature Indexes (UNI) to assess urban ecological performance. This paper introduces the UNI methodology and discusses strategic directions for its application in Korea. The UNI is grounded in the Driving forces-Pressures-State-Impact-Response framework and the Urban Bioshed Impact Areas model, enabling assessment of ecological impacts within and beyond city boundaries. It comprises six themes and 30 indicator topics. For Korea, we highlight priorities including indicator localization, data infrastructure development, and policy integration. Applying the UNI in Korea is expected to strengthen national biodiversity strategies and position cities as active contributors to global sustainability agendas.

Keywords: Urban biodiversity, Ecological indicators, Sustainability assessment, Nature-based solutions, Ecosystem services, Urban resilience

Introduction

Biodiversity is the fundamental foundation that sustains human survival, health, and quality of life. The Convention on Biological Diversity (CBD), which institutionalized this internationally, has established conservation goals since its entry into force in 1993, but rapid urbanization threatens its achievements (Chan, 2024). Over half of the world's population now lives in cities, projected to reach 70% by 2050 (UNDESA, 2019). This population concentration and land-use transformation are altering urban ecosystem structures and intensifying complex environmental risks stemming from the combination of physical development and climate change (Bonthoux & Chollet, 2024; Miller, 2005). In particular, various climatic and non-climatic factors such as heatwaves, floods, and air pollution accelerate habitat fragmentation and species loss within cities (Faeth *et al*., 2011; Oke *et al*., 2021; Soga & Gaston, 2016). Despite these vulnerabilities, cities are dual-natured spaces with the potential to become crucial sites for biodiversity conservation and ecosystem restoration. Some endangered species inhabit and depend on cities for survival (Ives *et al*., 2016; Soanes & Lentini, 2019), while urban nature—such as parks, gardens, and green corridors—provides diverse ecosystem services including cooling, flood mitigation, air purification, food supply, and recreation (Dobbs *et al*., 2014; Elmqvist *et al*., 2015). These natural elements maintain human-nature connections, creating positive effects that enhance well-

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being and conservation, thereby supporting the necessity of urban ecosystem management.

As the importance of urban ecosystems and biodiversity is emphasized, research analyzing species richness, habitat connectivity, and ecosystem service functions is actively conducted in various cities (Kendal *et al*., 2020). However, these studies have primarily focused on large cities in developed countries and temperate regions, and have been centered on birds and plants, leaving data on other taxonomic groups and developing countries still limited (Faeth *et al*., 2011; Luederitz *et al*., 2015). To address these limitations and assess biodiversity management at the urban level, the Secretariat of the CBD and Singapore's National Parks Board jointly developed the City Biodiversity Index (CBI; Singapore Index) (Deslauriers *et al*., 2018). While the CBI is a useful indicator for assessing the state of biodiversity and management efforts within cities, it struggles to encompass ecological impacts extending beyond urban boundaries or social and policy responses. Consequently, there is a growing need for a more comprehensive indicator that can holistically evaluate not only species and habitats within cities but also ecosystem services, human well-being, and governance (Pierce *et al*., 2024).

The global biodiversity agenda (Post-2020 Global Biodiversity Framework, Sustainable Development Goals, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, etc.) is expanding beyond conservation to include restoration and the realization of Nature's Contributions to People (NCP) (Díaz *et al*., 2015; Xie & Bulkeley, 2020). The role of cities in achieving these goals is increasingly vital, suggesting that urban governance must adopt innovative strategies beyond simple land-use planning, such as experimental approaches, urban wilding, and nature-based solutions (Cohen-Shacham *et al*., 2016; Xie & Bulkeley, 2020). Cities are now required to act not as passive spaces managing vulnerability, but as active agents driving global transition.

The International Union for Conservation of Nature (IUCN) developed the Urban Nature Indexes (UNI) to comprehensively assess the ecological performance of cities within this context (Pierce *et al*., 2024). The UNI is designed to assess the ecological footprint extending beyond the city itself, based on the Driving forces-Pressures-State-Impact-Response (DPSIR) model and the concept of urban bioshed impact areas (Bradley & Yee, 2015; Patrício *et al*., 2016; Pierce, 2022). Furthermore, by comprehensively considering not only species and habitats but also ecosystem services, human well-being, and governance responses, it functions as a standardized assessment framework linking cities to global biodiversity goals. Therefore, this paper aims to evaluate the applicability and limitations of the index by examining UNI's conceptual foundation, indicator system, and methodological structure, and analyzing international application cases. Furthermore, based on the results of its pilot application in Korean cities, it aims to propose strategic management directions for localizing the UNI and enhancing the ecological performance of cities.

Materials and Methods

Conceptual framework and structural design of the UNI

Development rationale and conceptual foundations

The UNI is an international standard assessment system developed by the IUCN. It serves as a tool for quantitatively evaluating and monitoring the state and changes in natural capital and ecosystem services at the urban level. The development of the UNI stemmed from the recognition that while the existing CBI is useful for measuring the status of biodiversity within cities, its application is constrained by local conditions such as city size, socio-

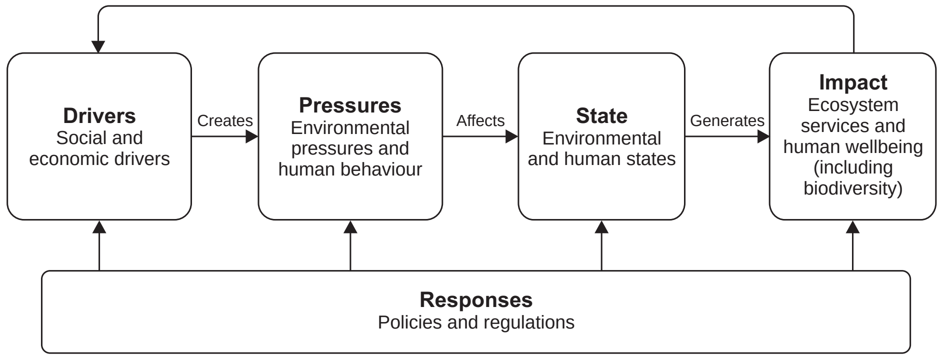

Fig. 1. Conceptual frameworks of the Urban Nature Indexes. Driving forces-Pressures-State-Impact-Response (DPSIR) model illustrating the feedback relationships between social drivers, environmental pressures, ecosystem states, impacts, and policy responses. Fig. 1 adapted from IUCN. The Urban Nature Indexes: Methodological Framework and Key Indicators; 2023, based on Bradley and Yee (2015).

economic context, and data availability. Consequently, the IUCN established an integrated indicator system to assess a city's ecological performance in a more systematic and standardized manner. UNI is designed based on two conceptual frameworks. First, it systematically reflects the complexity and causal structure of urban ecosystems by applying the DPSIR framework (Fig. 1) (IUCN, 2023). This model presents a five-stage causal structure: pressures originating from socio-economic drivers such as human health, safety, and welfare affect the state of the urban environment; the resulting impacts act upon ecosystem services and human well-being; and this leads to policy and institutional efforts to address these impacts. UNI's six themes (Drivers, Pressures, State, Impacts, Responses, Governance) were structured to reflect this causal flow. Second, it introduced the concept of urban bioshed impact areas, acknowledging that a city's ecological impacts extend beyond administrative boundaries to broader spatial scales (IUCN, 2023). Accordingly, UNI defines three spatial levels—① within the city (local scale), ② adjacent areas functionally connected to the city (bioregional scale), and ③ external areas linked to global supply chains and resource flows (global scale)—to establish the scope of influence for each indicator. This design enables UNI to simultaneously assess both a city's direct impacts and its linked impacts on distant regions. In summary, UNI integrates the causal structure of DPSIR with the spatial scale concept of the biosphere's sphere of influence. It serves as an integrated international standard assessment system capable of diagnosing a city's ecological performance across both time and space.

Structure and thematic composition

The UNI are composed of six themes and 30 detailed indicators based on the previously introduced DPSIR model to reflect the causal structure of urban ecosystems (Table 1). Each theme is designed to systematically diagnose the impacts of urban socio-economic activities on the natural environment, the resulting ecological responses, and societal countermeasures.

The first theme, 'Consumption Drivers,' assesses the fundamental drivers of social·economic activities—such as urban energy use and resource consumption—on ecosystems, specifically considering the indirect impacts these consumption patterns have on ecosystems outside the city. The second theme, 'Human Pressures,' evaluates direct pressures within cities, including various forms of environmental pollution and expansion, to identify the negative impacts of urbanization on ecosystem structure and function. The third theme, 'Habitat Status,' and the fourth theme, 'Species Status,' diagnose the physical habitat conditions and the state of biodiversity, respectively. This aims to evaluate the health of urban ecosystems through indicators such as habitat restoration, vegetation cover, green network connectivity, and changes in flora and fauna. The fifth theme, 'Nature's Contributions to People,' evaluates the ecosystem services provided by urban ecosystems. It measures social benefits such as citizen welfare, health, and quality of life, encompassing regulatory, provisioning, and cultural functions. Finally, 'Governance Responses' assesses urban governance capacity through policies, in-

Table 1. Structure of the Urban Nature Indexes framework

Theme	ID	Indicator topics
1. Consumption Drivers	1.1	Material consumption
	1.2	Harmful harvest & trade
	1.3	GHG emissions from energy
	1.4	Unsustainable diets
	1.5	Water withdrawal
2. Human Pressures	2.1	Sprawl
	2.2	Water pollution
	2.3	Noise pollution
	2.4	Light pollution
	2.5	Invasive species
3. Habitat Status	3.1	Land use/protection
	3.2	Ecosystem restoration
	3.3	Shorelines & riverbanks
	3.4	Vegetation cover
	3.5	Connectivity
4. Species Status	4.1	Animal species
	4.2	Plant species
	4.3	Functional diversity
	4.4	Microbiota
	4.5	Endemic species
5. Nature's Contributions to People	5.1	Exposure to nature
	5.2	Access to nature
	5.3	Human health
	5.4	Livelihoods
	5.5	Sacred nature sites
6. Governance Responses	6.1	Planning
	6.2	Laws & policy
	6.3	Education
	6.4	Management
	6.5	Incentives & participation

The Urban Nature Indexes are composed of six overarching themes—Consumption Drivers, Human Pressures, Habitat Status, Species Status, Nature's Contributions to People, and Governance Responses—each comprising five indicator topics (30 in total).
GHG, greenhouse gas.

stitutions, planning, and citizen participation, diagnosing the level of societal response to ecological issues identified in earlier stages. Thus, UNI perceives cities not merely as physical habitats but as socio-ecological systems where humans, nature, and policies interact. Consequently, each theme functions not as a list of individual indicators but as a component for analyzing a city's ecological performance in a causal and multi-layered manner.

Each detailed indicator follows a consistent format, comprising Aim, Definition, Guidance, Alternative Metrics, Resources, and Scoring Scheme. This structure enhances comparability between indicators and is designed for flexible application across cities with varying data availability. For example, the '1.1 Material consumption' indicator uses per capita solid waste generation as its primary metric, but may utilize per capita consumption-based ecological footprint as an alternative metric depending on city conditions. This standardized indicator design enables inter-city result comparisons and long-term monitoring, minimizing evaluator subjectivity while ensuring consistency in policy interpretation.

The UNI establishes a baseline for urban ecosystems through its initial assessment and identifies change trends using historical data or repeated assessments every three years. These trends can be categorized as no change, positive change, negative change, or insufficient data. The direction of change for each theme can be utilized to set priorities for urban policy and establish management strategies. Consequently, UNI's scoring system can track a city's ecological transition and scientifically present a development pathway toward becoming a sustainable and biodiversity-rich city.

Results

International applications and pilot implementation of the UNI

International applications: the Berlin case

The UNI is known to have been piloted in several cities, but the only officially validated assessment results currently available are those published by the IUCN for the Berlin case (IUCN, 2025). As Germany's capital, Berlin conducted a comprehensive assessment covering 23 detailed indicators across 6 themes, based on its extensive urban environment statistics and policy reports (Table 2) (IUCN, 2025). Data was collected from public databases such as Berlin's Senate Department for the Environment, Mobility, and Consumer Protection (SenUMVK) and the Federal Environment Agency (Umweltbundesamt). The evaluation results showed a trend toward sustainable transition in the 'Consumption Drivers' category, including efficient resource circulation management and a reduction in greenhouse gas emissions from energy use by approximately 17% in 2020 compared to 2019. In the 'Human Pressures' category, a baseline was established for environmental pressures such as urban expansion and noise/light pollution. The spread of the invasive species, the tree of heaven (*Ailanthus altissima*), was specifically identified as an ecological risk factor. The 'Habitat & Species Status' category confirmed high biodiversity, with the city maintaining a high urban green space ratio of approximately 59% and recording over 3,000 animal species and more than 1,200 plant species. However, results for some specific indicators (two habitat-related and one species-related) were not disclosed. In the 'Nature's Contributions to People' category, citizens' access to nature was favorable (approximately 40% of residents can access green space within 300 meters), and park usage rates were also high. However, indicators related to air quality remained at an intermediate level. In the 'Governance Responses' category, city-level green infrastructure and biodiversity management plans (e.g., GRaBS, Action Program for Urban Green Space) and citizen participation programs were well-established. However, evaluation results for the policy and legal/institutional sectors were absent, meaning the systematic foundation for governance as a whole was only partially assessed.

Overall, the Berlin case demonstrates that UNI is a practical tool capable of quantitatively diagnosing the multi-layered performance of urban ecosystems. In advanced cities with high data accessibility, the full set of UNI indicators could be effectively applied, enabling integrated evaluation across policy, planning, and educational programs. The absence of evaluation results for some indicators (e.g., 3.3, 4.4, 5.5, 6.1, 6.2) may stem from data gaps, but it is also possible they were excluded from assessment based on the city's capacity level.

Pilot evaluation in Seoul

To conduct a pilot assessment of the natural and ecological status among cities in the Republic of Korea, cities with well-established data and high data availability were reviewed. As a result, the UNI was calculated for Seoul Special City, the capital, using the methodology at (Table 3; SMG, 2025a, 2025b). Following the UNI's phased application principle, ten detailed indicators encompassing various sectors such as environment, climate, and green spaces were selected, considering the city's data availability and accessibility to administrative statistics. The data used for the indicators was extracted and compiled from sources including the Seoul Open Data Plaza (SMG, 2025a) and the Water Cycle Information Disclosure System (SMG, 2025b).

Evaluation results: under 'Consumption Drivers,' per capita solid waste generation (1.1) showed a decreasing trend from 0.014 kg/person/day in 2020 to 0.011 kg/person/day in 2023, while greenhouse gas emissions from

Table 2. Summary of Urban Nature Indexes indicator results for Berlin

Theme	ID	Indicator topics	Score
Consumption Drivers	1.1	Material consumption	Baseline measured
	1.3	GHG emissions from energy	Decreasing trend observed
	1.4	Unsustainable diets	Baseline measured
	1.5	Water withdrawal	Decreasing trend observed
Human Pressures	2.1	Sprawl	Baseline measured
	2.2	Water pollution	Baseline measured
	2.3	Noise pollution	Baseline measured
	2.4	Light pollution	Baseline measured
	2.5	Invasive species	Baseline measured
Habitat Status	3.1	Land use/protection	Baseline measured
	3.4	Vegetation cover	Baseline measured
Species Status	4.1	Animal species	Baseline measured
	4.2	Plant speceis	Baseline measured
	4.3	Functional diversity	Baseline measured
	4.5	Endemic species	Baseline measured
Nature's Contributions to People	5.1	Exposure to nature	Unchanged trend
	5.2	Access to nature	Baseline measured
	5.3	Human health	Baseline measured
	5.4	Llivelihoods	Baseline measured
	5.5	Sacred nature sites	Baseline measured
Governance Responses	6.3	Education	Baseline measured
	6.4	Management	Baseline measured
	6.5	Incentives & participation	Baseline measured

Data were obtained from the International Union for Conservation of Nature (IUCN) Urban Nature Indexes database and official materials provided by IUCN (IUCN, 2025).
GHG, greenhouse gas.

energy use (1.3) established a baseline of 3.16 t CO_2 in 2023, establishing a baseline. Under 'Human Pressures,' urban sprawl showed a mitigating trend, decreasing from 251 people/ha to 241 people/ha, while the noise indicator remained at a relatively high level of 54.4-56.6 db. In 'Habitat Status,' the protected area coefficient within the urban area decreased slightly from 0.558 in 2020 to 0.548 in 2024, while the green space ratio increased somewhat from 26.1% to 26.3%. This is judged to reflect the results of policies focused on qualitative management of existing green spaces and the creation of small-scale green spaces within living areas, rather than the expansion of new green areas. In the 'Nature's Contributions to People' category, citizens' access to nature (5.1) decreased to approximately 47 million people in 2022 but increased to about 6 million people in 2023, indicating that ecological accessibility within living areas was assessed as favorable.

Overall, the results of Seoul's pilot application reflect the characteristics of a large city with stable data accessibility and administrative statistics systems. While most of UNI's key indicators could be practically evaluated, some items could not be assessed due to limitations in data disclosure scope or format inconsistencies. However, these items are not deemed to be entirely absent; rather, they are considered difficult to use directly due to constraints in administrative procedures or access pathways.

Discussion

The UNI is an indicator system developed to comprehensively assess the structure, functions, and services of urban ecosystems. Its significance lies in its design to quantitatively evaluate natural assets and the contributions of nature—elements that have been relatively undervalued in existing environmental statistics and sustainability indicators. However, given the complex intertwining of urban ecological, social, and economic systems, various limiting factors are expected to arise during UNI applica-

Table 3. Results of the pilot application of the Urban Nature Indexes indicators in Seoul

<table>
<tr><th>ID</th><th>Indicator</th><th>Method</th><th>Result</th><th>Source</th><th>Score</th></tr>
<tr><td>1.1</td><td>Material consumption</td><td>Total waste volume (industrial, construction, municipal, designated waste)÷total urban population</td><td><table><tr><td colspan="4">Average daily solid waste generation per capita (kg)</td></tr><tr><td>2020</td><td>2021</td><td>2022</td><td>2023</td></tr><tr><td>0.014</td><td>0.014</td><td>0.012</td><td>0.011</td></tr></table></td><td>Seoul Open Data Plaza</td><td>+
Decreasing trend observed</td></tr>
<tr><td>1.3</td><td>GHG emissions from energy</td><td>Energy consumption by source (electricity, gas, district heating)×emission factor÷total urban population</td><td><table><tr><td>Per capita emissions (2023; t CO_2)</td></tr><tr><td>3.16</td></tr></table></td><td>Seoul Metropolitan City’s energy consumption</td><td>•
Baseline measured</td></tr>
<tr><td>1.5</td><td>Water withdrawal</td><td>Water supply volume÷total urban population</td><td><table><tr><td colspan="5">Daily water supply per person (L)</td></tr><tr><td>2020</td><td>2021</td><td>2022</td><td>2023</td><td>2024</td></tr><tr><td>300</td><td>303</td><td>303</td><td>302</td><td>290</td></tr></table></td><td>Seoul Open Data Plaza</td><td>+
Decreasing trend observed</td></tr>
<tr><td>2.1</td><td>Sprawl</td><td>Total population÷developed land area (Biotop map: roads, urbanized areas, etc.)</td><td><table><tr><td colspan="2">Average density (persons/ha)</td></tr><tr><td>2020</td><td>2025</td></tr><tr><td>251</td><td>241</td></tr></table></td><td>Seoul Open Data Plaza</td><td>+
Decreasing trend observed</td></tr>
<tr><td>2.2</td><td>Water pollution</td><td>Calculate the difference in total nitrogen values measured at the upper and lower reaches of the river</td><td><table><tr><td rowspan="2">Stream</td><td colspan="4">Total N (mg/L)</td></tr><tr><td>2021</td><td>2022</td><td>2023</td><td>2024</td></tr><tr><td>Cheonggye</td><td>0.53</td><td>0.36</td><td>0.57</td><td>0.11</td></tr><tr><td>Jungnang</td><td>−0.92</td><td>−1.75</td><td>−0.01</td><td>1.26</td></tr></table></td><td>Seoul Water Cycle Information Disclosure System</td><td>=
Unchanged trend</td></tr>
<tr><td>2.3</td><td>Noise pollution</td><td>Arithmetic mean of four daily noise measurements in green areas</td><td><table><tr><td>Year</td><td>Sites</td><td>Noise (dB)</td></tr><tr><td rowspan="3">2023</td><td>Olympic Velodrome</td><td>54.9</td></tr><tr><td>Pool</td><td>57.4</td></tr><tr><td>Musical fountain</td><td>57.5</td></tr><tr><td rowspan="3">2024</td><td>Olympic Velodrome</td><td>53.7</td></tr><tr><td>Swimming pool</td><td>55.2</td></tr><tr><td>Musical fountain</td><td>54.3</td></tr></table></td><td>Seoul website</td><td>+
Decreasing trend observed</td></tr>
<tr><td>3.1</td><td>Land use/ protection</td><td>Calculating the Protected Land Factor by assigning weights according to protection levels</td><td><table><tr><td colspan="2">Protected land factor</td></tr><tr><td>2020</td><td>2025</td></tr><tr><td>0.558</td><td>0.548</td></tr></table></td><td>Seoul Open Data Plaza</td><td>-
Negative trend observed</td></tr>
<tr><td>3.4</td><td>Vegetation cover</td><td>Tree and shrub area÷total urban area (Biotop map: vegetation)</td><td><table><tr><td colspan="2">Vegetation cover (%)</td></tr><tr><td>2020</td><td>2025</td></tr><tr><td>26.1</td><td>26.3</td></tr></table></td><td>Seoul Open Data Plaza</td><td>+
Positive trend observed</td></tr>
<tr><td>5.1</td><td>Exposure to nature</td><td>Estimate the total annual number of visitors to Hangang Parks</td><td><table><tr><td colspan="4">Total annual number of site visitors (×1,000 persons)</td></tr><tr><td>2020</td><td>2021</td><td>2022</td><td>2023</td></tr><tr><td>56,328</td><td>57,629</td><td>47,424</td><td>60,488</td></tr></table></td><td>Seoul Hangang Park Headquarters</td><td>+
Positive trend observed</td></tr>
<tr><td>5.3</td><td>Human health</td><td>Measure air quality (PM2.5) within the region</td><td><table><tr><td colspan="4">Average PM2.5 concentration (μg/m^3)</td></tr><tr><td>2020</td><td>2021</td><td>2022</td><td>2023</td></tr><tr><td>20.67</td><td>19.78</td><td>18.35</td><td>19.66</td></tr></table></td><td>Seoul Open Data Plaza</td><td>=
Unchanged trend</td></tr>
</table>

Source: SMG (2025a; 2025b).
GHG, greenhouse gas.

tion, including data availability, mismatches between administrative units and ecological spaces, and differences in social contexts (McPhearson *et al*., 2016). Particularly, the level of data infrastructure—a prerequisite for indicator calculation—varies significantly between countries and cities, potentially negatively impacting the comparability and reliability of the indicators.

The pilot evaluation results for Seoul analyzed in this study clearly demonstrate these structural characteristics. In large cities where data accessibility and administrative statistical systems are relatively well-established, UNI's key indicators could be practically evaluated. However, evaluation was limited for some items due to inconsistencies in the scope or format of data disclosure. This appears to stem more from constraints in administrative procedures or access pathways than from data absence. It is judged that most indicator calculations would be feasible if consultation procedures were followed with the agencies directly managing the data. Conversely, when examining the availability of the same indicators for small and medium-sized cities at the city and county levels (e.g., Suncheon, Seocheon), the proportion of data directly obtainable was only about 50%. This indicates that the presence of environmental measurements and data infrastructure conditions vary significantly depending on the size and budget level of the local government. Therefore, a supplementary process is necessary to flexibly adjust the indicator calculation method, considering the data gap between local governments, to enable evaluation even in environments with insufficient data. This goes beyond simply developing specialized indicators for each city; it involves establishing an alternative evaluation system tailored to the administrative and technical capacity levels of each local government.

Meanwhile, UNI is based on the premise that a city's ecological impact extends beyond administrative boundaries to adjacent ecological units. This spatial expansiveness signifies that cities do not exist as isolated units but are closely interconnected with water resources, air quality, land use, and other aspects of neighboring areas (Seto *et al*., 2012). Therefore, fundamental environmental improvement is difficult to achieve through internal management systems alone. Furthermore, while time-series measurable indicators such as water intake volume, energy consumption, noise pollution, and water quality pollution clearly demonstrate changes in the urban environment, structural constraints exist before these results translate into tangible improvements. While the current UNI is effective in diagnosing a city's environmental performance, the system for linking these results to policy implementation or citizen participation is relatively inadequate. To overcome these limitations, it is necessary to evolve into an action-oriented evaluation system that promotes policy realization and citizen participation. This requires concurrent efforts in interconnected management beyond city boundaries, changes in citizen behavior, and the establishment of collaborative governance among diverse stakeholders.

Based on this discussion, the following strategic approaches are required to apply UNI more effectively within the Korean context. First, since UNI is designed to allow indicator selection based on city size and data capabilities, Korean local governments should establish a differentiated indicator selection strategy reflecting each city's size, administrative capacity, and data infrastructure level, rather than uniformly applying all indicators. Second, to ensure reliability in inter-city comparisons, management must be based on a common data template with a consistent format and structure. Third, for UNI to be utilized in actual policy decision-making, it is essential to directly link the indicator results to existing policy frameworks like Korea Nature-based Solutions (K-NbS) and the National Biodiversity Strategy, converting them into actionable implementation and investment strategies. Finally, since most indicators are difficult to improve through policy measures alone, the practice foundation must be strengthened by linking evaluation results to citizen-participatory monitoring or community-based environmental management programs, ensuring they lead to positive change. These strategic considerations will form a crucial foundation for UNI to transcend being a mere evaluation tool and establish itself as a sustainable ecological management system for Korean cities.

Conclusion

This study systematized the conceptual foundation and structure of the UNI and examined its applicability and limitations at the urban level through case studies of Berlin and Seoul. The UNI, an international standard indicator system integrating the DPSIR model and the concept of the biosphere sphere of influence, was confirmed to enable spatiotemporal diagnosis of urban ecosystem structure, function, and services, as well as quantitative assessment of ecological performance and sustainability. Case analysis revealed that while large cities could calculate indicators relatively stably, medium and small cities exhibited limitations in applying some indicators due to constraints in data infrastructure and administrative systems. Future research should verify the applicability of all 30 indicators domestically, beyond the 10 applied in Seoul, and systematically analyze the standardization potential for data requirements, substitute indicators, and calculation units per indicator. Additionally, research is needed to examine the feasibility of indicator calculation across 17 metropolitan governments and major basic local governments, leading to the creation of a nationwide data availability map. Furthermore, developing a spatial analysis framework to address the mismatch between administrative boundaries and ecological space units is also proposed as a future task. Furthermore, for UNI to transcend a one-time diagnosis and be utilized for tracking long-term changes and comparative analysis between cities, a monitoring infrastructure must be established.

This infrastructure should include regular data updates and a system for linking and managing evaluation results. Ultimately, UNI possesses the potential to evolve beyond a tool for measuring a city's ecological performance into an action-oriented indicator system that connects policy implementation with citizen participation. It can become a core foundation for sustainable urban transformation. From this perspective, when developing K-NbS indicators, it is necessary to leverage UNI's structural strengths while designing a customized evaluation system that reflects each city's data foundation, shifts in citizen behavior, and local governance characteristics.

Author Contributions

Conceptualization: YC, SRK. Funding acquisition: YC, SRK. Investigation: YC. Methodology: YC. Validation: YC, SRK. Writing – original draft: YC. Writing – review & editing: YC, SRK.

Conflict of Interest

The authors declare that they have no competing interests.

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Green and Blue Space Contributions to IUCN NbS Challenges: A Review on Heat Mitigation and Flood Reduction

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ABSTRACT

The global significance of nature-based solutions (NbS) is increasingly emphasized, yet practical and evidence-based guidance on defining and implementing effective NbS strategies remains limited. This review synthesizes findings from twenty key empirical studies that examine the role of urban green and blue spaces (GBS) in addressing two of the IUCN's societal challenges: (1) climate change mitigation and adaptation, with a focus on urban heat reduction, and (2) disaster risk reduction, with a focus on urban flood mitigation. Evidence across the literature shows that GBS meaningfully reduce both surface temperatures and flood risks. The effectiveness of GBS is determined not only by expanding their coverage but also by designing interconnected ecological systems with optimized spatial configuration, vegetation structure, hydrological linkages, and by ensuring that they are positioned in the urban areas most vulnerable to heat and flooding. To enhance urban climate resilience, cities should adopt scale-appropriate design and placement strategies and integrate GBS within existing infrastructure networks. Future research should develop standardized performance metrics, assess long-term outcomes under climate change scenarios, and strengthen evidence-based urban planning that positions NbS as a central component of sustainable and resilient city development.

Keywords: Green and blue spaces, Nature-based solutions, Urban flood mitigation, Urban heat mitigation

Introduction

Rapid urbanization and climate change are intensifying environmental and social pressures on cities worldwide. Globally, more than half of the world's population now resides in urban areas, and this proportion is projected to reach approximately 68% by 2050 (United Nations, 2019). As urban populations continue to increase, expanding built-up areas accelerate the conversion of permeable surfaces into impervious ones, reducing infiltration and increasing runoff (Ongaga *et al*., 2024; Wu *et al*., 2020). The decline in urban green spaces and water bodies exacerbates multiple socio-environmental challenges, including the urban heat island effect, heightened flood risk, deteriorating air quality, and the loss of biodiversity (Saiz-Rodríguez *et al*., 2021).

Given these growing pressures, the International Union for Conservation of Nature (IUCN, 2016) identifies seven key societal challenges: (1) climate change mitigation and adaptation, (2) disaster risk reduction, (3) economic and social development, (4) human health, (5) food security,

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(6) water security, and (7) environmental degradation and biodiversity loss. To address these multifaceted challenges, nature-based solutions (NbS) have gained significant global attention. According to the IUCN (2016), NbS are defined as "actions that protect, sustainably manage, or restore natural or modified ecosystems to address societal challenges in an effective and adaptive manner, while simultaneously delivering benefits for human well-being and biodiversity." Although formally defined only recently, the underlying principles—such as wetland restoration, riparian conservation, and the integration of vegetation into urban design—have long been embedded in ecological management and landscape planning practices.

NbS encompass a broad and inclusive framework consisting of three major categories: (1) existing natural or protected ecosystems, (2) sustainably managed or restored ecosystems, and (3) newly created ecosystems. While this framework covers a wide range of approaches across different landscapes, this review focuses specifically on green and blue space (GBS)–based NbS within urban environments. These interventions—including parks, urban forests, waterways, wetlands, and constructed green infrastructure systems—represent some of the most widely implemented NbS strategies in cities.

The international community has also increasingly highlighted the expansion and restoration of urban GBS as a core component of sustainable urban development. The Kunming–Montreal Global Biodiversity Framework, adopted in 2022, establishes 23 global targets to be achieved by 2030; among these, Target 12 explicitly calls for enhanced access to GBS in urban areas (CBD, 2022), emphasizing the essential role of urban ecosystems in strengthening climate resilience and improving human well-being.

Despite the growing global emphasis on the importance of NbS, clear guidance on what makes an NbS effective and how such strategies should be designed and implemented in practice remains limited (IUCN, 2020). Rather than simply increasing the quantity of GBS, cities need a deeper understanding of how these measures should be strategically applied to address specific urban challenges. Accordingly, this study reviews a wide range of empirical research to examine evidence-based NbS applications, with particular emphasis on two of the IUCN's societal challenges: (1) climate change mitigation and adaptation, focusing on urban heat reduction, and (2) disaster risk reduction, focusing on flood mitigation. This research aims to synthesize quantitative evidence and to identify design and implementation strategies that maximize the effectiveness of urban GBS measures for climate resilience.

Materials and Methods

This research conducted a systematic literature review targeting peer-reviewed academic papers and official reports from international organizations published during the 2010-2025 period. Key databases (Web of Science, Scopus, PubMed, Google Scholar) were utilized, searching with the keywords "Urban green spaces", "Nature-based Solutions", "GBS", "Flood risk reduction", "Cooling effect", "Biodiversity", and "Climate Adaptation." The literature selection criteria were limited to studies presenting quantitative effects of urban green spaces and NbS. Out of a total of 157 papers, 20 core documents were ultimately selected for analysis (Fig. 1).

Results

Cooling effects of urban green and blue spaces

Evidence from ten key studies shows that urban GBS contribute meaningfully to surface temperature reduction (Table 1). Overall, the reviewed literature indicates that

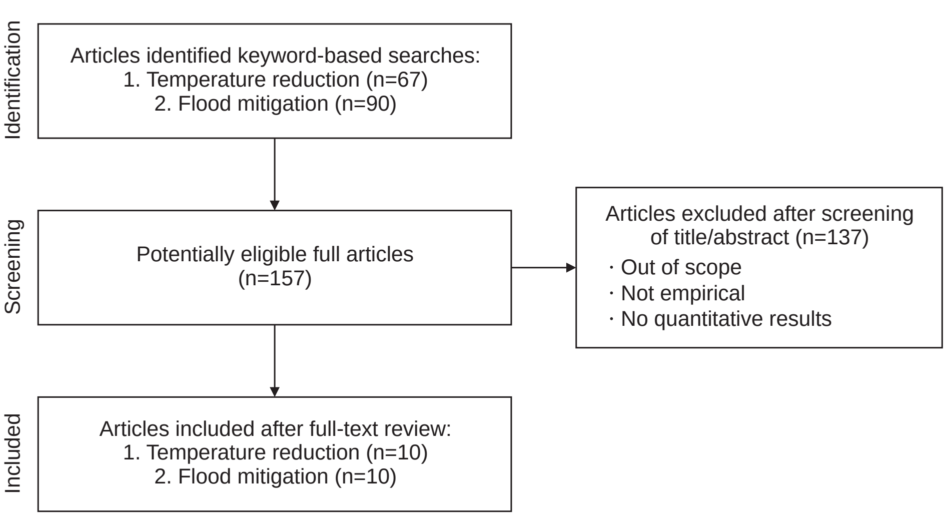

Fig. 1. Screening and selection flow diagram for green and blue spaces–temperature and flood mitigation studies.

Table 1. Summary of empirical studies on GBS contributions to urban surface temperature reduction

Societal challenges	Authors	Country	Types of GBS	Area (ha)	Outcome measure	Effect	Findings
Climate change mitigation and adaptation (urban surface temperature reduction)	Bowler *et al.*, 2010	Global (meta-analysis)	47 Urban green infrastructure (parks, trees, grass, green roofs)	0.02-525	ΔT	Daytime: 0.94°C cooler; nighttime: 1.15°C cooler	Across 47 eligible studies (74 identified), most observational evidence indicates green sites are cooler than nearby urban sites. The meta-analysis of park cooling effects (16 studies, 26 effect sizes) showed a consistent cooling effect during both day and night
	Cao *et al.*, 2010	Japan (Nagoya)	92 Parks	0.1-41.9	PCI	Spring (1.16 K), summer (1.30 K), autumn (0.43 K)	Larger parks showed stronger cooling (parks >2 ha produced PCI >~1.5 K); tree and shrub cover increased PCI, while grass land and bare soil reduced PCI
	Du *et al.*, 2017	China (Shanghai)	68 Parks	1-205	TA	3.02°C (0.78-5.2°C)	Significant negative correlation between green-space area and LST; threshold≈40 ha—cooling efficiency plateaus beyond this size; complex shapes lower LST
	Lin *et al.*, 2015	China (Beijing)	30 Parks	37-643	ΔT_{max}	2.3-4.8°C	Urban parks cooling extents vary widely from 35 to 840 m, increase generally with park size, show temperature reductions of about 2.3-4.8°C
	Yu *et al.*, 2017	China (Fuzhou)	435 Green patches	0.02-296.7	ΔLST	Water-connected greenspaces (6.38°C); non-connected (3.61°C)	The average LST reduction was 6.38°C for water-connected patches versus 3.61°C for non-connected patches, indicating an enhanced cooling effect of approximately 2.8°C
	Feyisa *et al.*, 2014	Ethiopia (Addis Ababa)	21 Parks	0.85-22.3	PCI, PCD	PCI: up to 6.72°C (mean 3.93°C); PCD: up to 224 m	Cooling effect determined by species, canopy cover, park size, and shape; temperature decreased by 0.02°C per 1% increase in canopy cover; PCI positively related to park area; *Eucalyptus* spp. showed the strongest cooling

Table 1. Continued

Societal challenges	Authors	Country	Types of GBS	Area (ha)	Outcome measure	Effect	Findings
	Chang and Li, 2014	Taiwan (Taipei)	60 Parks	0.01-39.7	LCHI, PCHI	LCHI: −3 to +3°C; PCHI: −2 to +2°C	Thermal gradients differ by park type and time; park size >5 ha → stronger external cooling; vegetation >30%, paved <50% → extended cooling
	Chen *et al.*, 2014	China (Beijing)	Urban green patches (trees, shrubs, grass, crops, river, lake)	Total 6,450 (35% of study area)	UCI	Strongest UCI: lake; moderate: trees, river (seasonally variable); weaker: shrubs and grass (especially in cold season)	Larger patch area, higher neighboring green proportion, and greater edge length are associated with stronger cooling, with effects most pronounced in summer
	Hamada & Ohta, 2010	Japan (Nagoya)	Heiwa Park	147 (60% forest, 7% grass)	ΔT	Max ΔT=1.9°C (July, 16:00); Min=−0.3°C (March noon); Cooling extent: 200-300 m at night; up to 300-500 m daytime (Aug-Oct)	Clear seasonal variation: stronger cooling in summer, weaker in winter; forest-cover ratio (within 200 m) significantly correlated with lower air temperature (−0.34°C per +10% forest cover)
	Monteiro *et al.*, 2016	United Kingdom (London)	8 Gardens & parks	0.2-12.1	UHI, cooling distance	Mean cooling intensity: 0.3-1.0°C, cooling extent: ~0 m for <0.5 ha, 30-120 m for 0.8-3.8 ha, 180-330 m for 10-12 ha	Cooling extent increases linearly with greenspace area; very small (<0.5 ha): negligible external effect; small (0.8-3.8 ha): 0.4-0.8°C cooling, 30-120 m reach; medium (10-12 ha): 0.6-1.0°C cooling, up to 330 m reach

GBS, green and blue space; ΔT, temperature difference, $T_{urban}-T_{park}$; PCI, park cool intensity; TA, temperature drop amplitude; ΔT_{max}, maximum temperature difference; LST, land surface temperature; PCD, park cooling distance; LCHI, local cool/heat island intensity; PCHI, park cool/heat island intensity; UCI, urban cooling island; UHI, urban heat island.

Table 2. Summary of empirical studies on GBS contributions to urban flood reduction

Societal challenges	Authors	Country	Types of GBS	Area	Outcome measure	Effect	Findings
Disaster risk reduction (flood reduction)	Song *et al.*, 2019	China (Shenzhen)	LID infrastructure (permeable pavements, green roofs, concave green fields *et al.*)	37.68 km^2	Model simulation (Absorption, recovery, adaptation capacity)	Absorption time (0.00-10.40 h → 2.15-11.21 h); recovery capacity (76.38% → 98.19%); 35% of previously flooded areas no longer flooded	LID implementation significantly improved drainage infrastructure's absorption and recovery capacities; to maximize effectiveness, LID structures should be targeted toward low-lying, flood-prone zones, where flood volume and inundation depth are highest and infrastructure is weakest
	Richter & Dickhaut, 2023	Germany (Hamburg)	BGR systems	Four 220 m^2 roofs and two 135 m^2 roofs	Long-term hydrological monitoring (2017-2023)	64-74% of annual precipitation retained; peak runoff coefficients extremely low (Cp=0.02-0.04)	BGRs significantly reduced and delayed stormwater runoff, outperforming conventional extensive GRs; long-term storage systems provided the strongest retention and longest detention times
	Palermo *et al.* 2023	Italy	Green walls	Two vegetation boxes per 100×100 cm panel	RC; TSO	RC range: 0-81.6% (mean: 42%); TSO range: 4-35 min (mean: 12 min)	The modular green wall system demonstrated good stormwater retention capacity
	Giermek, 2015	South Africa (Cape Town; Liesbeek River)	Small urban wetland (Valkenberg Wetland)	1.54 km^2 surface area (wetland adjacent to urban river)	Peak flow hydrographs	Peak flow reduction: up to 42% during sharp, flashy events; ~20% during long-duration events	The urban wetland attenuated peak flows by accepting a portion of stormwater during high-intensity rainfall. Attenuation was most effective for short, sudden flood peaks; highlights the potential of small urban wetlands as part of sustainable urban drainage, though insufficient alone to prevent major floods

Table 2. Continued

Societal challenges	Authors	Country	Types of GBS	Area	Outcome measure	Effect	Findings
	Laub *et al*., 2024	USA (San Antonio, Texas)	2 Bioretention basins	Drainage areas 5.5 ha & 0.4 ha	Hydrograph analysis (peak flow, rise/fall rates, duration)	Peak flow reduced by >80% on average; flashiness (rate of rise/fall) reduced by 80-90%	Bioretention basins substantially reduced peak flow; basins increased runoff duration and delayed hydrograph response, reducing downstream flood risk
	Jeon *et al*., 2021	South Korea (Cheonan)	Rain garden	Catchment area (476 m^2)	5-year field monitoring (23 rainfall events)	Runoff reduction: initially 98% to 88% after 5 years	The rain garden still achieved an 88% runoff reduction after five years, indicating sustained high hydrological performance
	Staccione *et al*., 2024	Italy (Metropolitan City of Milan)	GI (urban parks, green roofs, green spaces, green corridors *et al*.)	Milan metropolitan area	Pluvial flood hazard modelling	Damage reduction up to ~60%; population exposed reduced 40% with only +25% GI	Expanding the GI network by 25% cuts building damages by 50% and reduces population exposure by 40%. Combined GI expansion (green city) is more effective than using green roofs or ground GI alone
	Peng *et al*., 2025	UK (London Borough of Enfield)	7 Constructed wetlands	Catchment area (41 km^2, 37 km^2)	River flow analysis	High flows decreased by 18-23%, while low flows increased by 35-50%	Constructed wetlands lowered peak flows during storm events and increased baseflows during dry periods, contributing to a more stable urban water regime

Table 2. Continued

Societal challenges	Authors	Country	Types of GBS	Area	Outcome measure	Effect	Findings
	Gupta *et al*., 2024	India (Brahmaputra River catchment)	Rejuvenated wetlands	190,000 km^2 (catchment scale)	Streamflow reduction (%), water level reduction (m), flood-threat level occurrence	Peak streamflow reduced by 5.1-8.3%; flood-threat events reduced by up to 30-65% (at major cities)	Rejuvenated & actively managed wetlands significantly attenuate flood peaks across the basin especially when connected to nearby streams and operated with controlled releases
	Khalafallah *et al*., 2025	Serbia (Tamnava Basin)	Retention ponds	730 km^2 (basin scale)	Flood area reduction (%), flood volume reduction (%), flood damage reduction (%)	Flood area reduced by 20-27%, flood volume reduced by 28-35%, flood damage reduced by 40-45%	Retention ponds significantly reduced basin-scale flood hazards under current & future climates; larger or multiple ponds (in series) performed best

GRs, green roofs; GBS, green and blue space; LID, low-impact development; BGR, blue–green roof; RC, runoff coefficient; TSO, time to start outflow; GI, green infrastructure.

cooling performance is influenced by multiple factors including patch size, vegetation structure, and surrounding land-use characteristics among others.

One of the most consistent determinants of cooling effect is the size of green spaces, with most empirical studies indicating that larger patches exhibit both higher cooling intensity and wider spatial cooling reach. An analysis of 92 parks in Japan by Cao *et al*. (2010) showed that parks smaller than 2 ha produced little to no cooling, whereas meaningful cooling emerged only beyond this threshold. In particular, parks larger than 10 ha displayed the strongest cooling effects. Similarly, Monteiro *et al*. (2016), examining eight greenspaces in the United Kingdom, reported that very small parks (<0.5 ha) generated minimal cooling of about 0.3°C and exhibited virtually no cooling beyond their boundaries. Small parks (0.8-3.8 ha) cooled surrounding areas by roughly 0.4-0.8°C, while medium parks (10-12 ha) produced stronger cooling of 0.6-1.0°C and extended their influence over distances of 180-330 m. However, increases in park size do not yield unlimited gains. Du *et al*. (2017), analyzing 68 parks in Shanghai, identified a diminishing marginal effect around 40 ha, beyond which additional area provided limited extra cooling.

Vegetation structure also strongly influenced the magnitude of urban cooling. Overall, tree-dominated green spaces exhibited substantially greater temperature-reduction effects than shrub- or grass-dominated areas (Cao *et al*. 2010; Chang & Li, 2014; Feyisa *et al*., 2014). For example, Bowler *et al*. (2010) noted that several included studies reported stronger cooling effects in parks with substantial tree cover compared with grass-dominated areas. Feyisa *et al*. (2014) found that land-surface temperature decreased by approximately 0.02°C for every 1% increase in canopy cover, demonstrating that higher canopy density substantially enhances local cooling. Similarly, Hamada and Ohta (2010) reported a strong negative correlation between forest-cover ratio (within 200 m) and daytime air temperature, suggesting that greater forest cover effectively mitigates urban heat. Regarding species composition, broadleaf trees were generally more effective than conifers. Feyisa *et al*. (2014) found that *Eucalyptus* spp. provided the strongest cooling, while *Cupressus* and *Grevillea* (coniferous and semi-evergreen species) were less effective. Hamada and Ohta (2010) observed that mixed deciduous–evergreen stands within the study park exhibited higher specific humidity in summer, which contributed to daytime cooling.

The cooling performance of GBS is also influenced by the characteristics of adjacent land-use types. Yu *et al*. (2017) found that green spaces adjacent to or connected with water bodies showed a markedly enhanced cooling effect compared with green-only areas. Green–blue combinations reduced land surface temperatures by about 6.38°C relative to built-up areas, which is nearly 3°C stronger than the cooling observed in green spaces without water adjacency, and they also exhibited larger cooling extents and intensities. Similarly, Chen *et al*. (2014) reported that larger green patches and a higher proportion of neighboring green areas were associated with stronger surface urban cool island effects. Among green types, rivers and lakes exhibited the most pronounced cooling, and tree-dominated patches were consistently cooler than areas dominated by shrubs or grass.

Green and blue spaces contributions to urban flood mitigation

Urban GBS are widely utilized in urban areas as effective measures for flood mitigation. Following the micro-, meso-, and macro-scale classification proposed by Esraz-Ul-Zannat *et al*. (2024), this review organizes ten representative papers accordingly to examine how different types of NbS contribute to urban flood mitigation across spatial scales (Table 2).

Micro-scale GBS, including blue roofs, green roofs, green walls, permeable pavements, and rainwater harvesting, function primarily at the building or block level to directly reduce stormwater runoff. Across the reviewed studies, these measures consistently demonstrated substantial improvements in drainage performance. For example, Song *et al*. (2019) reported that implementing LID-type GBS across a 37.68 km^2 area in Shenzhen increased absorption duration, enhanced recovery capacity from 76.38-98.19%, and eliminated flooding in 35% of previously flooded areas. For blue–green roofs, Richter and Dickhaut (2023) reported that these systems retained 64-74% of rainfall, reduced peak runoff to extremely low levels (C_p=0.02-0.04), and delayed discharge for several hours. For green walls, Palermo *et al*. (2023) found that a modular living wall system performed robustly under 32 simulated rainfall events, with runoff coefficients spanning 0-81.6% and outflow initiation delayed by 4-35 minutes. Such performance indicates that even individual micro-scale units can exert measurable influence on stormwater behavior during storm events.

Meso-scale GBS operate at the neighborhood or sub-catchment scale and include systems such as swales, green streets, infiltration trenches, rain gardens, detention ponds, retention ponds, and sand filters. These GBS elements extend hydrological regulation beyond the immediate installation site by reducing peak flows, enhancing infiltration, and stabilizing runoff dynamics across connected urban drainage networks. The reviewed studies consistently show that meso-scale measures provide substantial buffering capacity during storm events. For example, Giermek (2015) showed that small urban wetlands in Cape Town reduced peak flows by up to 42% during flash events and approximately 20% during longer-duration storms. Laub *et al*. (2024) further showed that two small bioretention basins in Texas reduced peak flow by approximately 77-83% on average and decreased hydrograph flashiness by 83-93%. In the case of rain gardens, Jeon *et al*. (2021) showed that the system maintained a consistent 88% reduction in runoff over a five-year monitoring period. These results suggest that meso-scale bioretention facilities can provide long-term, stable buffering capacity under repeatedly occurring storm events in real urban environments.

Macro-scale GBS encompass large-scale ecological and hydrological interventions—such as riparian buffers, urban agriculture, urban forests, and constructed wetlands—that operate at the metropolitan or basin scale. These measures influence hydrological regimes across expansive regions, providing structural and long-term flood mitigation benefits. Staccione *et al*. (2024) demonstrated through city-scale pluvial flood modeling that expanding green infrastructure by 25% across the Milan metropolitan area could reduce building damages by 50%, lower population exposure by 40%, and decrease flood damages by up to 60% under extreme rainfall conditions. At even larger spatial extents, multiple studies showed that wetland-based and retention systems are highly effective in reducing basin-scale flood hazards (Gupta *et al*., 2024; Khalafallah *et al*., 2025; Peng *et al*., 2025). For example, Gupta *et al*. (2024) reported that rejuvenated wetlands across the 190,000 km^2 Brahmaputra River basin reduced peak streamflow by 5.1-8.3% and lowered the frequency of flood-threat events by 30-65% in major cities. Collectively, these studies demonstrate that macro-scale GBS deliver the most substantial and durable reductions in urban and regional flood risk, particularly when implemented as interconnected ecological networks spanning catchments, river corridors, and metropolitan systems.

Discussion

NbS are increasingly recognized as having strong potential to address multiple societal and environmental challenges, yet further empirical evidence is needed to guide their optimal design and application across different scales and contexts (e.g., Chausson *et al*., 2020; IUCN, 2020; Seddon *et al*., 2020; United Nations Environment Programme, 2021). In response to this need, the present review synthesizes empirical findings on NbS in urban environments, demonstrating that GBS play a critical role in addressing two of the IUCN's major societal challenges—climate change mitigation and adaptation, and disaster risk reduction—through measurable reductions in urban heat and flooding.

A review of ten empirical heat-mitigation studies shows that cooling benefits are maximized when ecological systems are designed to be interconnected and to include optimized spatial configurations, diverse vegetation structures, and hydrological connectivity. This suggests that not only the quantitative expansion of green–blue spaces but also their qualitative characteristics are critical for enhancing cooling performance. For example, park's internal thermal condition is the strongest determinant of the surrounding air temperature (Chang & Li, 2014), indicating that vegetation quality within a park plays a decisive role in regulating near-park microclimates. In particular, the shading capacity and evapotranspiration potential of tree canopies were identified as the primary drivers of enhanced cooling, indicating the importance of increasing tree-canopy cover while reducing the amount of bare soil in green spaces. Moreover, because cooling effects typically extend about 35-840 m from individual parks (Hamada & Ohta, 2010; Lin *et al*., 2015), distributing multiple medium-sized green patches throughout the urban is likely to provide broader city-wide cooling benefits than concentrating vegetation in a single location.

For flood mitigation, GBS implemented at micro-, meso-, and macro-scales each play complementary and mutually reinforcing roles. Even individual micro-scale units can measurably influence stormwater behavior during rainfall events. Because they can be deployed cost-effectively and in a highly distributed manner across dense urban areas, micro-scale NbS are particularly suitable for managing localized pluvial flooding. Their performance is further enhanced when installations are strategically positioned in low-lying or flood-prone zones, where flood volumes, inundation depths, and infrastructure vulnerabilities are greatest (Song *et al*., 2019). At the meso scale, NbS moderate stormwater volumes, delay hydrograph responses, and strengthen flood resilience at the district level—especially when they are hydrologically integrated with existing stormwater networks and natural flow pathways. Macro-scale GBS provide the most substantial and durable reductions in urban and regional flood risk, particularly when implemented as interconnected ecological networks spanning catchments, river corridors, and metropolitan systems. These large-scale interventions shape hydrological regimes, enhance storage capacity, and redistribute runoff across broader landscapes, thereby offering long-term flood mitigation benefits that smaller-scale interventions alone cannot achieve (Gupta *et al*., 2024).

Despite these insights, several limitations should be acknowledged when interpreting the findings of this review. The cited empirical studies (e.g., London, Milan, and Shenzhen) encompass diverse climatic contexts, and the effectiveness of GBS is likely to vary substantially across climate regimes. In monsoon regions such as Korea, where rainfall is highly concentrated during the summer months, the flood-mitigation efficiency of GBS may differ markedly from those observed in arid, temperate, or oceanic climates. This climatic heterogeneity was not explicitly addressed in the reviewed studies, representing a limitation. Moreover, the synthesis presented here does not fully account for the influence of urban morphological factors—such as building density, street canyon geometry, and prevailing wind pathways—which are known to mediate both the intensity and spatial reach of GBS-induced cooling and hydrological effects. Given these limitations, the application of GBS for heat and flood mitigation should be guided by empirical evidence tailored to local climatic conditions, urban structures, and hydrological settings. Future research would benefit from comparative, multi-city analyses that explicitly examine how climate, morphology, and spatial configuration interact to determine GBS performance across scales.

Conclusion

This review demonstrates that urban GBS play a critical role in addressing two of the IUCN's major societal challenges—climate change mitigation and adaptation, and disaster risk reduction—through measurable reductions in urban heat and flooding. Across the reviewed studies, the effectiveness of GBS depends strongly on spatial scale, ecological configuration, and the biophysical characteristics of both the intervention site and the surrounding landscape. These findings highlight that the value of NbS lies not only in increasing the quantity of urban GBS but also in designing interventions that function effectively as interconnected ecological systems. To maximize climate resilience, cities must consider scale-appropriate placement, vegetation structure, connectivity, and the integration of GBS into existing urban infrastructure. Future research should build on these insights by developing standardized metrics for assessing NbS performance, monitoring long-term outcomes under climate change scenarios, and supporting evidence-based urban planning that integrates NbS as a central strategy for sustainable and resilient city development.

Author Contributions

Conceptualization: SRK. Acquisition of data: SC. Writing – original draft: SRK, SC. Writing – review & editing: SRK, SC, BRK.

Conflict of Interest

The authors declare that they have no competing interests.

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Assessment of the Relationship Between ProtConn and Biodiversity Management: Evidence Gaps and Research Directions

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ABSTRACT

The Protected Connected land indicator (ProtConn) and the Species Protection Index (SPI) are adopted under Target 3 of the Kunming–Montreal Global Biodiversity Framework to represent structural connectivity and species-level conservation outcomes, respectively. However, empirical evidence linking ProtConn to observed biodiversity outcomes remains limited. This study synthesizes ecological theory, international policy frameworks, and existing literature to clarify the conceptual relationship between ProtConn and SPI and to assess the feasibility of future empirical linkage analyses. The results indicate that ProtConn primarily functions as a structural condition indicator describing protected area network configuration, whereas SPI captures biological conservation outcomes, highlighting a clear distinction between structural conditions and ecological responses. Furthermore, this study demonstrates that nationally standardized biodiversity datasets in the Republic of Korea are spatially and taxonomically compatible with ProtConn-based analyses. These findings identify critical empirical gaps and provide a methodological foundation for future quantitative research examining the relationship between protected area connectivity and biodiversity conservation outcomes.

Keywords: Biodiversity monitoring, Ecological connectivity, Global Biodiversity Framework, Protected area networks, Protected Connected land indicator, Species Protection Index

Introduction

Kunming–Montreal Global Biodiversity Framework (GBF) Target 3 calls for conserving at least 30% of terrestrial, inland water, and marine areas by 2030 through effectively and adequately connected protected areas and other effective area-based conservation measures (Convention on Biological Diversity [CBD], 2022). Compared with the former Aichi Target 11, GBF Target 3 places greater emphasis not only on the extent of protected areas but also on their quality and connectivity, increasing the demand for indicators capable of quantitatively assessing protected area connectivity.

In response to this demand, Protected Connected land indicator (ProtConn) has emerged as the most widely applied global indicator for evaluating the structural connectivity of protected area networks (Saura *et al*., 2018). ProtConn is grounded in landscape ecology and metapopulation theory and represents the structural characteristics

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of protected area networks. Its four components—Within, Contig, Unprot, and Trans—capture internal connectivity within protected areas, physical connectivity among adjacent protected areas, functional connectivity across non-adjacent protected areas through the surrounding matrix, and transboundary connectivity, respectively (Saura *et al*., 2017). These components are theoretically linked to key ecological mechanisms that support biodiversity persistence, including species movement, population rescue effects, and the maintenance of gene flow (Hanski, 1998).

Within the GBF Target 3 monitoring framework, ProtConn is defined as a structural condition indicator, whereas the Species Protection Index (SPI) is defined as an outcome indicator reflecting conservation success in terms of species range coverage (United Nations Environment Programme World Conservation Monitoring Center [UNEP-WCMC] & International Union for Conservation of Nature [IUCN], 2024). Although these indicators are reported in parallel to represent the "condition–outcome" logic of conservation policy, no empirical studies have examined their statistical relationship at national scales. The Protected Planet Report 2024 likewise presents ProtConn and SPI side by side but does not specify how structural connectivity relates to observed biodiversity outcomes (UNEP-WCMC & IUCN, 2024).

Existing research has primarily focused on estimating ProtConn values and describing their spatial or temporal variation. Saura *et al*. (2017; 2018; 2019) presented global assessments and time-series analyses of ProtConn but did not investigate whether increases in ProtConn are associated with improved species distributions, increased species richness, or reduced extinction risk. While some studies suggest that connectivity may indirectly influence ecosystem stability or habitat quality (Castillo *et al*., 2020; Zhao *et al*., 2022), direct species-based empirical analyses remain scarce.

Despite the availability of nationally standardized, high-resolution biodiversity datasets in Korea, empirical studies linking ProtConn with biodiversity indicators have not yet been conducted domestically or internationally. This study addresses this gap by clarifying the conceptual scope and limitations of ProtConn within the GBF Target 3 framework and by assessing whether existing national biodiversity datasets in Korea provide a feasible foundation for future empirical ProtConn–SPI or ProtConn–biodiversity linkage analyses.

Materials and Methods

This study adopts a theoretical and methodological review approach to examine the conceptual relationship between ProtConn and biodiversity indicators. First, internationally validated literature and official policy reports were systematically reviewed to clarify the definition of ProtConn, the ecological significance of its components, and the characteristics of country-level estimates, with a particular focus on Saura *et al*. (2017; 2018; 2019). To establish the theoretical foundations of ProtConn as a structural connectivity indicator, key ecological theories related to connectivity—including metapopulation theory (Hanski, 1998), island biogeography, and dispersal and gene flow theory—were reviewed. In addition, policy-oriented documents, including the Protected Planet Report 2024 (UNEP-WCMC & IUCN, 2024), were analyzed to examine the respective roles of ProtConn and the SPI as component indicators under the GBF Target 3 monitoring framework, and to identify current international limitations in empirical linkage analyses between these indicators.

Furthermore, rather than conducting empirical comparisons, this study performed a data feasibility assessment to evaluate the potential for future ProtConn–SPI or ProtConn–species indicator analyses in Korea. This assessment examined the spatial resolution, temporal coverage, taxonomic scope, and spatial unit compatibility of datasets from the National Ecosystem Survey (National Institute of Ecology; NIE), species occurrence records from the National Institute of Biological Resources (NIBR), and species inventory and ecological survey data produced by the Korea National Park Service (KNPS). The analysis focused on whether these datasets can be spatially aligned with ProtConn values at common grid units, thereby enabling future quantitative analyses of relationships between protected area connectivity and biodiversity indicators.

Results

ProtConn is widely applied as a global indicator for quantifying the structural connectivity of protected area networks (Saura *et al*., 2017; 2018). It consists of four components—Within, Contig, Unprot, and Trans—each capturing a distinct aspect of network structure, including internal connectivity within protected areas, connectivity among adjacent protected areas, functional connectivity across non-adjacent protected areas through the surrounding matrix, and transboundary connectivity (Table 1). These components describe the spatial configuration and potential coherence of protected area systems but do not directly measure biodiversity outcomes.

International assessments report substantial variation in ProtConn values among countries. According to CBD synthesis reports (CBD, 2021a; 2021b; 2021c), Germany exhibits relatively high ProtConn values (35.1%), while the Republic of Korea shows lower connectivity (approximately 9.0%), and Japan displays intermediate values (14.8%). These differences reflect variation in national topography, land-use patterns, and the spatial configuration of protected area systems.

Table 1. Ecological significance of ProtConn components

ProtConn component	Definition	General contribution (%)	Most relevant target	Key limitations
Within	Connectivity within individual protected areas	40-60	Large protected areas; wide-ranging species	Does not reflect connectivity between areas
Contig	Connectivity through physically adjacent protected areas	20-35	All species; particularly important for species with low mobility	Limited to directly adjacent areas
Unprot	Connectivity through non-adjacent protected areas within dispersal distance	15-30	Species with medium-high dispersal ability	Species-specific diffusion parameters required
Trans	Transboundary connectivity	5-15	Migratory species; species whose range crosses borders	Data availability issues; international cooperation required

ProtConn, Protected Connected land indicator.

To assess the feasibility of empirical linkage analyses between ProtConn and biodiversity indicators, this study examined three nationally standardized biodiversity data sources in Korea: the National Ecosystem Survey conducted by the NIE (2024), national biodiversity statistics compiled by the NIBR (2025), and species inventory data produced by the KNPS (2023).

The National Ecosystem Survey provides nationwide, grid-based biodiversity data derived from systematic field surveys, covering major taxonomic groups including plants, mammals, birds, amphibians, reptiles, fish, and invertebrates. Its spatial structure allows direct alignment with ProtConn values calculated at comparable spatial units, enabling potential overlay analyses of species richness and taxon-specific occurrence patterns. National biodiversity statistics published by NIBR synthesize verified species occurrence records and official inventories, documenting 61,230 species in Korea as of 2024. These statistics provide standardized indicators on total species richness, threatened species occurrence, and taxonomic composition at national and subnational scales. Species inventory data compiled by KNPS integrate systematic natural resource surveys across 23 national parks and document 23,777 species across diverse taxonomic groups. Although these data do not represent continuous population-level time series, they provide spatially explicit species richness information at the protected area scale.

Together, these datasets demonstrate that nationally standardized biodiversity data in Korea are spatially and taxonomically compatible with ProtConn-based analyses. While this study does not perform statistical linkage analyses, the results demonstrate that Korea possesses a sufficiently robust and structured biodiversity data infrastructure to support future quantitative evaluations of the relationship between ProtConn and biodiversity indicators.

Discussion

ProtConn is an internationally recognized connectivity indicator for protected area networks and is theoretically expected to contribute to biodiversity conservation. Ecological theories, including metapopulation dynamics and gene flow, consistently demonstrate that connectivity plays a critical role in sustaining species persistence (Hanski, 1998). However, despite this strong theoretical foundation, empirical evidence demonstrating that higher ProtConn values lead to measurable improvements in biodiversity indicators remains limited. Accordingly, ProtConn should be interpreted primarily as a structural indicator that characterizes enabling conditions for conservation rather than as a direct measure of conservation performance.

This structural role is reflected in the way ProtConn characterizes protected area networks through multiple dimensions of connectivity. Rather than representing biological responses directly, ProtConn components describe how protected areas are spatially configured and potentially connected within landscapes. As summarized in Table 1, national-scale applications commonly show that internal connectivity within protected areas contributes most strongly to overall ProtConn values, whereas connectivity mediated through non-adjacent or transboundary protected areas generally accounts for a smaller proportion (Saura *et al*., 2017; Hilty *et al*., 2020; UNEP-WCMC & IUCN, 2024). These contribution ranges represent general structural tendencies observed across countries and should not be interpreted as causal effects on biodiversity outcomes.

Each ProtConn component is also associated with inherent limitations. Internal connectivity does not capture interactions among separate protected areas, adjacency-based connectivity is restricted to directly neighboring sites, connectivity through unprotected matrices relies on assumptions regarding species dispersal ability, and transboundary connectivity is constrained by data availability and international coordination. These limitations highlight that ProtConn alone cannot explain species-level conservation outcomes, underscoring the need for a conceptual framework that explicitly links structural connectivity to ecological mechanisms and biodiversity indicators.

Building on this need, Fig. 1 presents a conceptual framework proposed in this study that integrates protected area network structure, ecological theory, and biodiversity outcome indicators. By characterizing protected area configuration through ProtConn and linking it to established ecological mechanisms—such as species

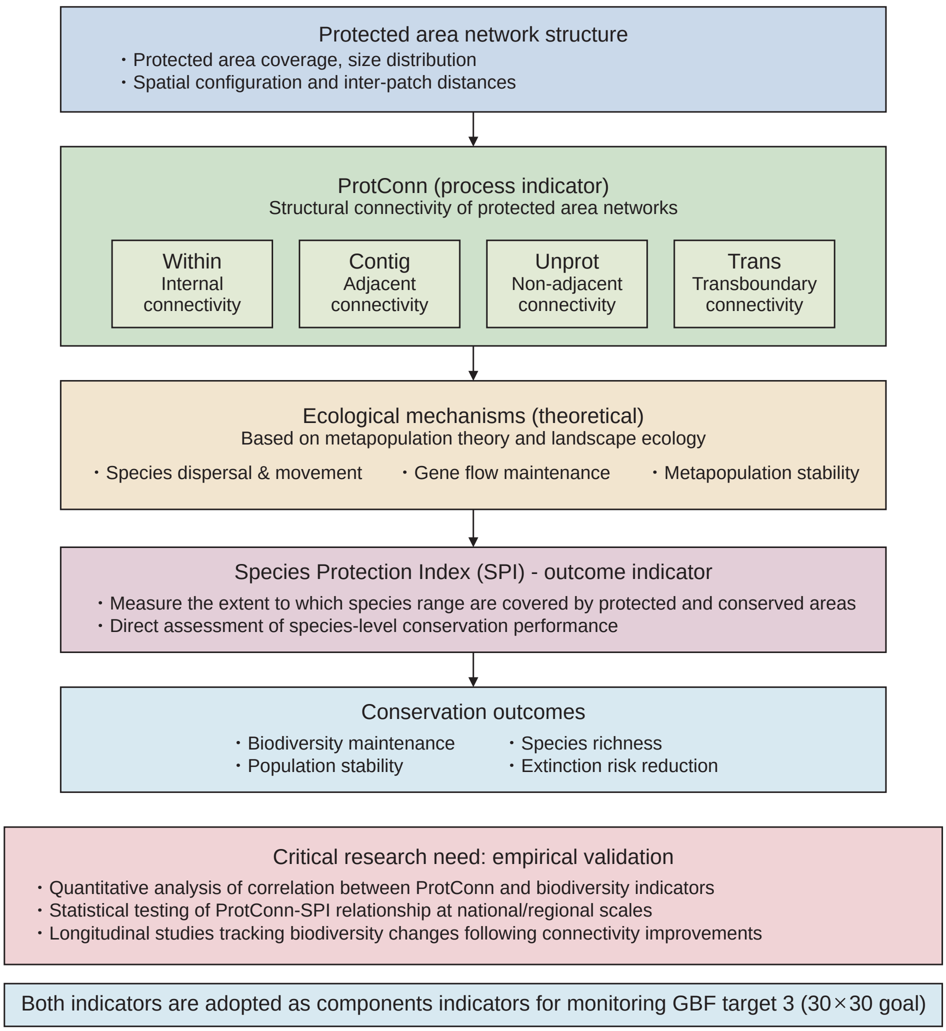

Fig. 1. Conceptual framework illustrating the theoretical relationship between Protected Connected land indicator (ProtConn) and Species Protection Index (SPI) in biodiversity conservation assessment. ProtConn acts as a process indicator measuring the structural connectivity of protected area networks through four components (Within, Contig, Unprot, Trans). SPI functions as an outcome indicator directly assessing species-level conservation performance. Pathways linking these indicators through ecological mechanisms (species dispersal, gene flow, metapopulation stability) are grounded in theoretical frameworks from landscape ecology and metapopulation theory. However, direct empirical evidence that ProtConn increases lead to measurable biodiversity improvements remains limited. Dotted lines indicate relationships requiring further empirical validation. Both indicators are recognized as component metrics for monitoring progress toward Global Biodiversity Framework (GBF) Target 3. This framework highlights key research gaps, particularly the need for quantitative studies integrating spatial connectivity data with biodiversity monitoring datasets at the national scale where comprehensive ecological survey data are available (e.g., Korea's National Institute of Ecology National Natural Environment Survey, National Institute of Biological Resources species occurrence records, and Korea National Park Service long-term monitoring data).

dispersal, gene flow, and metapopulation stability—the framework illustrates how structural connectivity may create conditions under which species-level conservation outcomes can be evaluated using outcome indicators such as the SPI. Importantly, this framework is conceptual in nature and is intended to clarify logical linkages rather than to depict empirically validated causal relationships.

The theoretical basis for these linkages is further synthesized in Table 2, which situates the proposed ProtConn–SPI framework within established ecological theory. While major theoretical perspectives—including metapopulation dynamics, island biogeography, and landscape ecology—strongly support the importance of connectivity for population persistence and species distributions, Table 2 also highlights important conceptual gaps. In particular, several connectivity-related processes, such as gene flow and source–sink dynamics, are not directly captured by outcome indicators focused on species range coverage. This reinforces the interpretation that ProtConn and SPI represent complementary, rather than interchangeable, dimensions of conservation assessment.

In this context, SPI provides a complementary outcome indicator that directly measures the extent to which species' geographic ranges are covered by protected areas. When considered alongside ProtConn, SPI enables examination of structure–outcome relationships in conservation planning, consistent with the GBF Target 3 monitoring framework (UNEP-WCMC & IUCN, 2024). Nevertheless, empirical analyses directly linking ProtConn and SPI remain scarce, highlighting a critical research gap.

Korea is particularly well positioned to address this gap, given the availability of nationally standardized biodiversity datasets, including the National Ecosystem Survey conducted by the NIE, biodiversity statistics compiled by the NIBR, and species inventory data produced by the KNPS Together, these datasets provide a robust foundation for future empirical analyses examining whether areas characterized by higher structural connectivity also exhibit higher species richness or greater representation of threatened species.

In conclusion, ProtConn serves as a robust indicator for characterizing the structural foundation of protected area networks and plays a central role in monitoring progress toward GBF Target 3. However, its contribution to biodiversity conservation outcomes cannot be fully assessed without empirical validation against outcome-based indicators. By integrating ProtConn, ecological theory, and outcome indicators within a coherent conceptual framework, this study clarifies the interpretive scope of connectivity indicators and outlines a structured pathway for future evidence-based conservation research.

Author Contributions

Conceptualization: SRK. Funding acquisition: YC, SRK. Investigation: SRK. Methodology: YC, SRK. Validation: YC, SRK. Writing – original draft: SRK. Writing – review & editing: YC.

Table 2. ProtConn–SPI connectivity assessment based on ecological theory

Theoretical framework	Key predictions	Empirical support level	ProtConn-SPI relevance
Metapopulation theory	Connected habitat patches support more viable populations through settlement-extinction dynamics and structural effects	Strong - Extensive evidence across multiple taxa and systems	High - Predict that connectivity should enhance species persistence and range occupancy
Island biogeography theory	Connected protected areas support higher species richness through enhanced colonization and reduced extinction	Strong - Well supported in actual islands and habitat fragments	Moderate - Primarily predicts species richness rather than range extent
Source-sink dynamics	Connectivity allows source populations to shape the demographic structure of sink populations	Moderate - Documented in multiple systems but difficult to measure	Moderate - Related to population maintenance but indirectly linked to range extent
Gene flow theory	Connectivity maintains genetic diversity and adaptive potential through gene flow	Strong - Genetic studies consistently show connectivity effects	Low - Genetic diversity is not directly measured by SPI
Principles of landscape ecology	Landscape composition influences ecological processes at multiple spatial scales	Strong - Extensive theoretical and empirical foundation	High - ProtConn explicitly applies landscape ecology principles

ProtConn, Protected Connected land indicator; SPI, Species Protection Index.

Conflict of Interest

The authors declare that they have no competing interests.

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Development of a Red List of Ecosystems-Nature based Solutions Integrated Decision Matrix for Policy Priority Setting

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ABSTRACT

This study presents an integrated decision-making matrix linking the International Union for Conservation of Nature (IUCN) Red List of Ecosystems (RLE) assessment framework with Nature-based Solutions (NbS) societal challenges for 36 ecosystem types defined in South Korea. We developed systematic mapping rules between RLE threat categories (land use change, hydrological modification, climate change, pollution, overexploitation, and invasive species) and seven NbS contribution areas (climate mitigation, climate adaptation, disaster risk reduction, water security, food security, biodiversity, and socioeconomic development). Our analysis revealed that wetland, estuarine, and coastal ecosystems under hydrological modification and reclamation pressure prioritize water security and disaster risk reduction-centered NbS; forest, grassland, and agricultural ecosystems experiencing fragmentation and conversion pressure prioritize biodiversity and socioeconomic/food security-centered NbS; and climate-vulnerable montane and cryogenic ecosystems prioritize climate adaptation and disaster risk reduction-centered NbS. The matrix proposes 2-3 core operational indicators for each ecosystem type to enhance implementation and monitoring practicality, and when combined with RLE risk assessments, can serve as a tool to strengthen objectivity in policy priority decisions. By presenting a national-level standardized framework linking ecosystem threat diagnosis with solution application, this study is expected to contribute to evidence-based ecosystem management policy development.

Keywords: Decision matrix, Ecosystem types, Nature-based Solutions, Priority setting, Red List of Ecosystems, Threat factors

Introduction

In the face of accelerating global climate crisis and biodiversity loss, systematic ecosystem assessment and effective conservation and restoration strategy development have emerged as core national environmental policy priorities (Díaz *et al.*, 2019; IPBES, 2019). The International Union for Conservation of Nature (IUCN) has been operating the Red List of Ecosystems (RLE) system since 2013 for quantitative assessment of ecosystem collapse risk (Bland *et al.*, 2017; Keith *et al.*, 2013), while simultaneously establishing and disseminating the concept of Nature-based Solutions (NbS) as an international standard since 2016 to address societal challenges using ecosystem services (Cohen-Shacham *et al.*, 2016; IUCN,

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2020). The RLE assesses ecosystem distribution decline, environmental degradation, and disruption of biotic interactions through five criteria (A-E), classifying risk into eight categories from Collapsed (CO) to Least Concern (LC) (Rodríguez *et al.*, 2015). The 2024 revised Guidelines Version 2.0 provides detailed assessment guidance for major collapse drivers including climate change, fragmentation, hydrological modification, pollution, overexploitation, and invasive species (Keith *et al.*, 2024). NbS represents an integrated approach to address major societal challenges through ecosystem-based solutions, with the IUCN Global Standard presenting a design and verification framework through eight criteria and 28 indicators (IUCN, 2020; Seddon *et al.*, 2021).

South Korea exhibits complex ecological characteristics with diverse ecosystem types including forests (64%), agricultural lands (20%), urban areas (7%), and wetlands (5%) (National Institute of Ecology, 2024), facing multiple threats from habitat loss due to rapid urbanization and industrialization, ecosystem disruption from climate change, and hydrological system alterations. Over the past 50 years, 35% of coastal wetlands have been lost, subalpine coniferous forests are experiencing mass mortality from climate change (Kim *et al.*, 2019; Park *et al.*, 2024; Yoo *et al.*, 2020), and riverine ecosystems have reached critical levels of fragmentation due to estuarine barrages and weir construction (National Institute of Environmental Research, 2024). The Ministry of Environment and National Institute of Ecology published a national ecosystem typology in 2024, defining 36 representative ecosystem types based on the IUCN Global Ecosystem Typology (GET) system (Keith *et al.*, 2020; 2022; National Institute of Ecology, 2024). This typology encompasses terrestrial (8 forests, 3 agricultural lands, 2 grasslands, 1 settlement), freshwater (5 wetlands, 6 rivers, 5 lakes), and marine (6) ecosystems, providing detailed descriptions of endemic biota, environmental characteristics, biotic interactions, and major threats for each type. However, the linkage with NbS approaches that can effectively address these threats has not yet been concretized.

While systematic linkage between ecosystem threat assessment (RLE) and solution application (NbS) is essential for effective ecosystem management, standardized methodologies integrating these two frameworks remain absent (Nicholson *et al.*, 2019). RLE provides a powerful tool for diagnosing ecosystem risk levels and major threat factors but does not prescribe specific management actions or solutions, whereas NbS offers solutions to various societal challenges but lacks systematic guidance on which NbS to prioritize for which ecosystems (Chausson *et al.*, 2020). The theoretical basis for RLE-NbS linkage can be found in adaptive ecosystem management and ecosystem services concepts (Folke *et al.*, 2016). Ecosystem health and functionality form the foundation for ecosystem service provision, which in turn determines NbS effectiveness (Kumar *et al.*, 2021). Therefore, ecosystem status diagnosis through RLE should be the starting point for NbS design, with particular importance placed on threat factor-specific tailored solution application.

International interest in linking ecosystem assessment and management is growing, with the EU Green Deal and Biodiversity Strategy 2030 presenting ecosystem restoration and NbS expansion as core policies (European Commission, 2020). China is linking its ecological redline system with ecological restoration projects under its ecological civilization construction policy, while Japan has integrated Ecosystem-based Disaster Risk Reduction into its national disaster prevention strategy (Renaud *et al.*, 2016). The Post-2020 Global Biodiversity Framework sets a target of restoring 30% of degraded ecosystems by 2030, emphasizing the importance of scientific priority setting (Convention on Biological Diversity, 2022). While Korea has established ecosystem restoration and NbS expansion as major tasks in its 5th National Biodiversity Strategy (2024-2028), specific priority setting and implementation strategies remain insufficient (Ministry of Environment, 2023).

This study aims to standardize major threat factors for 36 ecosystem types in Korea according to RLE guidelines, derive priority NbS contribution areas corresponding to each threat factor, and develop an integrated matrix presenting core decision levers and operational indicators for each ecosystem type. Through this framework, we seek to support policy makers and practitioners in performing decision-making under a consistent framework from ecosystem threat diagnosis through solution application to monitoring. By presenting the first national-level standardized tool linking ecosystem threats with solutions, this study is expected to contribute to the advancement of Korea's ecosystem management policy. The developed matrix can provide a methodological framework applicable to other countries or regions. Ultimately, this study aims to contribute to biodiversity conservation and sustainable development goal achievement through evidence-based ecosystem management.

Materials and Methods

Study scope and data sources

The analysis targets 36 ecosystem types documented in the "National Ecosystem Typology of Korea" published by the Ministry of Environment and National Institute of Ecology in 2024 (National Institute of Ecology, 2024). This typology applies the IUCN GET system (Keith *et al.*, 2020; 2022) adapted to Korea's ecological characteristics, comprising 14 terrestrial ecosystem types (8 forests, 3 agricultural lands, 2 grasslands, 1 settlement), 16 freshwater ecosystem types (5 wetlands, 6 rivers, 5 lakes), and

6 marine ecosystem types. Each ecosystem type is linked with IUCN GET codes to enable international comparison. For RLE assessment framework and threat category standardization, we referenced the Keith *et al.* (2024) "Guidelines for the application of IUCN Red List of Ecosystems Categories and Criteria: version 2.0," which systematizes major ecosystem collapse drivers into six categories. NbS contribution area classification was based on seven societal challenge areas presented in the IUCN Global Standard for Nature-based Solutions (International Union for Conservation of Nature, 2020).

Threat factor standardization and classification

We employed a 3-step process to classify threat factors for each of the 36 ecosystem types into RLE guideline standard threat categories. First, we extracted keywords from the threat factor sections of each ecosystem type definition and matched them with the six major RLE threat categories. Second, we consolidated similar threat factors into standardized terminology. Third, we incorporated Korea's specific ecological context in the threat factor standardization process. For example, while oak wilt disease internationally falls under the invasive species category, in Korea it acts as a complex factor associated with climate change, thus we classified it as a "climate change + invasive species" composite threat.

To ensure objectivity in the threat factor extraction process, ecology experts independently performed keyword coding. Discrepancies were reviewed based on the definitions in the IUCN RLE Guidelines (v2.0) to reach a consensus, and inter-coder agreement was established through cross-validation.

Development of NbS contribution area mapping rules

Mapping rules linking RLE threat factors and NbS contribution areas were systematically established through a literature review (2015-2024) using keywords such as "Ecosystem threat" and "Nature-based Solutions," prioritizing studies aligned with the IUCN Global Standard criteria to reflect direct threat impacts and ecosystem functions. Mapping rules were established according to the following principles: (1) direct response principle: prioritizing societal and environmental challenges directly affected by each threat factor; (2) ecosystem function-based principle: mapping NbS areas considering major services and functions provided by ecosystems; and (3) multiple benefit consideration: selecting 1-3 priority contribution areas reflecting that one NbS approach can simultaneously address multiple societal challenges (Seddon *et al.*, 2020).

Decision lever and operational indicator setting

We established applicable decision levers (conservation, restoration, management) for each ecosystem type and developed corresponding operational indicators. Decision levers were differentiated according to current ecosystem status and threat levels, while operational indicators were developed following SMART principles but designed to link with Korea's existing ecosystem monitoring systems (Aldridge and Colvin, 2024; Doran, 1981). Operational indicators were finally selected based on data availability from national monitoring systems (Ministry of Environment, National Institute of Ecology) and policy responsiveness. For riverine ecosystems, for example, we linked with existing aquatic ecosystem health assessment indicators such as river continuity index, water quality grades, and riparian vegetation width (National Institute of Environmental Research, 2024).

Integrated matrix construction

We integrated threat factor standardization, NbS mapping rules, decision levers, and operational indicators to construct a decision-making matrix for 36 ecosystem types. The matrix was designed to include ecosystem type codes and names, RLE standard threat categories (1-3 major threats), priority NbS contribution areas (1-3 areas), core decision levers (conservation/restoration/management), and operational indicators (2-3 quantitative indicators). The constructed matrix incorporated composite threat categories considering interactions between climate change and other threat factors, specifying threat combinations with strong interactions.

Results

Distribution of major threat factors by ecosystem type

Analysis of threat factors for 36 ecosystem types revealed six RLE threat categories appearing in various combinations. The most frequent threat was land use change and fragmentation, identified in 29 ecosystems (80.6%), followed by climate change in 22 (61.1%), pollution in 21 (58.3%), hydrological modification in 18 (50.0%), invasive species in 14 (38.9%), and overexploitation in 10 (27.8%) ecosystems (Table 1). In 14 terrestrial ecosystem types, land use change (85.7%) and climate change (71.4%) were identified as major threats, with 6 of 8 forest ecosystem types including climate change as a major threat. For subalpine and boreal coniferous forests, climate change appeared as the sole major threat, reflecting these ecosystems' high vulnerability to temperature rise and precipitation pattern changes (Kim *et al.*, 2019; Park *et al.*, 2024; Yoo *et al.*, 2020). In 16 freshwater ecosystem types, hydrological modification (87.5%) emerged as the primary threat, followed by pollution (75.0%) and land use change (68.8%). Land use change appeared as a major threat in all 6 marine ecosystem types (100%), with mudflats, salt marshes, and estuaries particularly experiencing direct habitat loss from reclamation and land conversion (Davidson, 2014).

Threat-NbS mapping patterns

Mapping analysis between RLE threat factors and NbS contribution areas derived systematic response patterns (Table 2). Land use change and fragmentation threats showed strong linkages with biodiversity loss and socioeconomic development areas, as habitat loss and fragmentation directly cause biodiversity decline and reduced ecosystem service provision capacity affects local economies and livelihoods (Díaz *et al.*, 2019). Hydrological modification threats were primarily mapped to water security and disaster risk reduction areas, reflecting how hydrological system changes from dams, weirs, and estuarine barrages directly affect water supply stability and flood/drought regulation capacity (Vörösmarty *et al.*, 2010). Climate change threats were linked to climate adaptation and disaster risk reduction areas, pollution to human health and water security, invasive species to biodiversity loss and food security, and overexploitation to food security and socioeconomic development areas respectively.

Table 1. Distribution of major threat factors by ecosystem realm

Ecosystem	Terrestrial (n=14)	Freshwater (n=16)	Coastal (n=6)
Land use change	12 (85.7)	11 (68.8)	6 (100.0)
Hydrological modification	2 (14.3)	14 (87.5)	2 (33.3)
Climate change	10 (71.4)	8 (50.0)	4 (66.7)
Pollution	6 (42.9)	12 (75.0)	3 (50.0)
Invasive species	8 (57.1)	4 (25.0)	2 (33.3)
Overexploitation	3 (21.4)	5 (31.3)	2 (33.3)

Values are presented as number (%).

These mapping patterns reflect the intrinsic characteristics of threat factors and their impact mechanisms on ecosystem services, clearly presenting societal challenges that should be prioritized in NbS design. Ecosystems exposed to multiple threats particularly showed the need for integrated application of multiple NbS areas.

Decision matrix by ecosystem groups

We classified 36 ecosystem types into five groups based on threat characteristics and priority NbS areas, deriving differentiated management strategies (Table 3). The first group comprises climate-vulnerable montane ecosystems including subalpine coniferous forests, boreal coniferous forests, and alpine shrublands, prioritizing climate adaptation and biodiversity conservation as NbS areas with conservation and adaptive management as core levers. The second group consists of hydrologically dependent freshwater ecosystems including permanent freshwater wetlands, large rivers, small streams, and lakes, prioritizing water security and disaster risk reduction as NbS areas with restoration and management as main levers. The third group encompasses coastal transitional ecosystems including mudflats, salt marshes, estuaries, and sand dunes, centering on disaster risk reduction and biodiversity with parallel conservation and restoration strategies. The fourth group comprises productive landscape ecosystems including rice paddies, crop fields, orchards, and pastures, prioritizing food security and socioeconomic development with sustainable management as the core lever. The fifth group includes urban and settlement ecosystems such as urban parks, street trees, and urban streams, focusing on human health and climate adaptation through green infrastructure expansion and ecological management.

Table 2. Mapping matrix between RLE threat factors and NbS contribution areas

RLE threat factor	1st NbS	2nd NbS	3rd NbS	Core mechanism
Land use change	Biodiversity	Socioeconomic development area	Food security	Habitat loss → Biodeversity decline → Deterioration of ecosystem services
Hydrological modification	Water security	Disaster risk reduction areas	Biodiversity	Hydrological system change → Instability of water supply → Flood/drought
Climate change	Climate adaptation	Disaster risk reduction areas	Biodiversity	Temperature/precipitation change → Ecosystem function change → Extreme events
Pollution	Human health	Water security	Biodiversity	Pollution accumulation → Health scathe → Water resource pollution
Invasive species	Biodiversity	Food security	Socioeconomic development area	Competition from native species → Changes in ecosystem structure → Declining productivity
Overexploitation	Food security	Socioeconomic development area	Biodiversity	Resource depletion → Decreased production capacity → Economic losses

RLE, Red List of Ecosystems; NbS, Nature-based Solutions.

Table 3. Integrated decision-making matrix by ecosystem group

Ecosystem group	Representative type	Major threat	Priority NbS	Core lever	Operational indicator
Montane-climate vulnerable	Subalpine coniferous forest	Climate change	Climate adaptation, biodiversity	Conservation+adaptive management	Tree line, endemic species trends
Freshwater-hydrologically dependent	Permanent wetlands, large rivers	Hydrological modification, pollution	Water security, disaster risk reduction	Restoration +management	River continuity index, water quality grades
Coastal-transitional	Salt marshes, mudflats	Land use change, climate change	Disaster risk reduction, biodiversity	Conservation +restoration	Habitat area, migratory bird population
Landscape-productive	Rice paddies, crop fields, orchards	Land use change, climate change	Food security, socioeconomic development	Sustainable management	Eco-friendly certification rate, biodiversity
Unban/settlement	Urban parks, street trees	Land use change, pollution	Human health, climate adaptation	Green infrastructure	Green space ratio, urban heat island intensity

NbS, Nature-based Solutions.

Discussion

The RLE-NbS integrated matrix developed in this study represents the first national-level standardized tool systematically linking ecosystem threat diagnosis with solution application. Unlike previous studies focusing on individual ecosystems or specific threats (Chausson *et al.*, 2020; Kumar *et al.*, 2021), this matrix presents an integrated approach encompassing 36 ecosystem types, enabling systematic ecosystem management at the national level. The standardization of threat factors particularly enables inter-ecosystem comparison and priority setting, with hydrological modification appearing as a major threat in 87.5% of freshwater ecosystems providing scientific evidence for establishing river continuity restoration as a national priority. This approach aligns with river restoration target setting under the EU Water Framework Directive (European Commission, 2000), consistent with international policy trends. Furthermore, systematic mapping with NbS contribution areas enables ecosystem-specific tailored solution application, supporting efficient allocation of limited resources and generation of multiple benefits. These research outcomes can be directly utilized in developing national strategies for achieving Post-2020 Global Biodiversity Framework targets.

The major characteristics of Korean ecosystems derived from our analysis clearly demonstrate the complex impacts of rapid development and climate change. Land use change emerging as the most widespread threat (80.6%) reflects Korea's high development pressure and limited land area, with 100% of coastal ecosystems exposed to land use change threats particularly showing the cumulative historical impacts of reclamation and land conversion (Choi, 2014). This suggests habitat conservation and ecological network establishment as top policy priorities, emphasizing the need for integrated approaches to national land and environmental planning. The high hydrological modification threat (87.5%) in freshwater ecosystems reflects the results of large-scale river management including the Four Major Rivers Project and construction of over 16,000 weirs and dams (Grill *et al.*, 2019), indicating river continuity restoration and environmental flow provision as urgent tasks. Climate change affecting 61.1% of ecosystems with particularly high vulnerability in montane and boreal ecosystems suggests the need for climate refugia conservation and connectivity enhancement to secure species migration corridors (Morelli *et al.*, 2016). These complex threat patterns demonstrate the limitations of single-sector approaches and highlight the need for integrated management strategies.

Systematic implementation strategies are required for effective policy application of this matrix. First, a two-dimensional priority-setting system combining RLE risk grades with the matrix should be established to select

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ecosystems with high risk grades (endangered [EN], critically endangered [CR]) and exposure to multiple threats as top priorities. Second, inter-sectoral collaborative governance considering NbS multiple benefits should be established, requiring policy coordination and budget integration among relevant ministries including Environment, Oceans and Fisheries, Forest Service, and Land and Transport. Integrated governance is particularly essential for wetland and river management linking water security, disaster risk reduction, and biodiversity. Third, clarifying priority NbS areas for each ecosystem can strengthen linkages with various international funding sources including climate funds, biodiversity funds, and disaster risk reduction funds. Fourth, adaptive management systems adjusting management strategies through regular monitoring and feedback using operational indicators should be established, with scenario-based management considering climate change uncertainty being particularly important.

This study has several limitations suggesting future research directions. First, incomplete RLE risk grade assessments for ecosystem types constrains actual priority setting, requiring integrated application with the matrix following completion of national-level RLE assessments. Second, quantification of interactions and cumulative impacts between threat factors was not achieved, requiring additional research to evaluate synergistic effects of composite threats such as climate change-invasive species and pollution-eutrophication (Brook *et al.*, 2008). Third, quantitative assessment of NbS effectiveness is lacking, requiring future cost-effectiveness analysis of NbS interventions according to ecosystem types and threat characteristics. Fourth, dynamic changes in social-ecological systems were not sufficiently reflected, necessitating model development integrating feedback between socioeconomic drivers such as urbanization, population change, and land use conversion with ecosystem changes (Folke *et al.*, 2016). Fifth, regional characteristics and stakeholder participation were not adequately considered, requiring development of regional-level detailed matrices and establishment of participatory decision-making mechanisms. Despite the spatial scale mismatch between the macro-scale RLE and micro-scale NbS, the proposed matrix serves as a “meso-scale framework” that bridges the gap between national priority setting and local-level implementation.

By developing an integrated decision-making matrix for 36 Korean ecosystem types linking the IUCN RLE threat assessment system with NbS solutions, this study provides a consistent decision-making framework from ecosystem threat diagnosis to solution application. The developed matrix supports evidence-based ecosystem management policy development and can serve as a tool facilitating priority setting and inter-sectoral collaboration under limited resources. It is particularly expected to contribute directly to developing national strategies for achieving the Post-2020 Global Biodiversity Framework and Sustainable Development Goals. Future continuous improvement of the matrix through completion of RLE risk assessments, quantification of threat interactions, and NbS effectiveness evaluation, along with integration into national biodiversity strategies and carbon neutrality policies, is needed. Ultimately, we hope the RLE-NbS linkage framework presented in this study can provide a methodological model not only for Korea but also for other countries facing similar ecological challenges, contributing to global biodiversity conservation and sustainable development.

Conclusion

This study developed an integrated decision-making matrix linking RLE-based threat diagnosis with NbS solutions for 36 ecosystem types in South Korea. This framework will contribute to transitioning fragmented ecosystem management policies toward evidence-based integrated management. In particular, we identified the need for priority policy intervention in freshwater ecosystems suffering from severe hydrological modification and forest ecosystems vulnerable to climate change. Despite limitations such as the lack of quantification of threat interactions and scale mismatches, this study is significant in providing a practical roadmap for implementing national biodiversity strategies. Future research should focus on refining the matrix based on accumulated RLE assessment data and developing detailed guidelines reflecting regional characteristics.

Author Contributions

Conceptualization: SRK. Data curation: SH. Formal analysis: SH, SRK. Supervision: SRK. Visualization: SH, SRK. Writing – original draft: SH. Writing – review & editing: SH, SRK.

Conflict of Interest

The authors declare that they have no competing interests.

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Assessing a Reptile Species Protection Index for the Republic of Korea under Climate Change

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ABSTRACT

This study assessed changes in the Species Protection Index (SPI) for reptiles in the Republic of Korea under climate change. We integrated nationwide survey data to build species distribution models (SDM) for 18 reptile species and assessed their potential habitats under current and future climate scenarios (Shared Socioeconomic Pathway [SSP]: SSP2-4.5 and SSP5-8.5). The SDM performed well, with a mean area under the curve of 0.965 (range 0.869-0.999). By overlaying the predicted potential habitats with protected areas, we calculated Species Protection Scores for individual species and a taxon-level SPI for reptiles. The current SPI was 26.74 when all species were included, and 28.16 when ecosystem-disturbing (invasive) species were excluded. When the Species Conservation Target was adjusted to reflect the Republic of Korea context, these increased to 36.62 and 38.53, respectively. Under both future scenarios, SPI values declined through the mid-century (~2050) and then increased again in the late century (2060-2090). Ecosystem-disturbing (invasive) species initially exhibited lower SPI values but tended to overtake non-invasive species in the long term, underscoring the need to manage their incursions within protected areas. Overall, the findings support designating additional climate-informed protected areas alongside national and global 30% expansion targets.

Keywords: Biodiversity, Climate change scenarios, Conservation policy, Protected areas, Species distribution model

Introduction

The World Economic Forum identified climate change and biodiversity loss as risks threatening humanity over the next decade in its "Global Risks 2023" report, which outlines threats facing the world (World Economic Forum, 2023). Habitat changes for Earth's species due to climate change are progressing very rapidly (Chen *et al.*, 2011). Due to differing response speeds among individual species, interactions between species may cease, and new interactions may emerge (Pecl *et al.*, 2017). Within this climate-changing environment, effective conservation, restoration, and enhanced habitat connectivity are essential to boost species adaptability (Intergovernmental Panel on Climate Change [IPCC], 2022). In particular, there is a need to redefine priority areas for protected regions considering future climate conditions (Jones *et al.*, 2016).

Approximately 20% of the world's reptiles are currently estimated to be threatened with extinction (Böhm *et al.*, 2016), with habitat loss due to excessive development being the primary cause (Böhm *et al.*, 2016). Furthermore, future climate scenarios predict declines in reptile species diversity across many regions, making climate change an emerging threat (Biber *et al.*, 2023). Most terrestrial ectotherms lack sufficient tolerance for environments ex-

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ceeding their survival temperatures. Therefore, to adapt to climate warming, they need increased access to diverse habitats that allow escape from extreme high temperatures (Sunday *et al.*, 2014).

The Species Protection Index (SPI) is an indicator that can assess the conservation status of species, not just the area of protected areas, and can play a crucial role in assessing species conservation status at the national and global levels (Jetz *et al.*, 2022; Kim *et al.*, 2024). SPI was adopted as a component indicator for Target 3 of the 2022 Kunming-Montreal Global Biodiversity Framework (GBF; UNEP-WCMC, 2022). The SPI is assessed annually at the national level worldwide through the Map of Life (Map of Life, 2024). The SPI calculation can be performed independently at the national level, and the species or protected area information currently used in Map of Life may be updated or replaced. The SPI information currently provided by Map of Life is not based on data held by domestic public institutions and has limitations in that it does not reflect the latest data. Therefore, the interpretation of SPI values and results can vary due to differences in species habitat area assessment methods, weighting for endemic species, and the incorporation of the latest species survey data (Kim *et al.*, 2024).

In the Republic of Korea, research on current and climate change-induced reptile habitats is underway (Do *et al.*, 2022; Shin *et al.*, 2024), but studies assessing reptile SPI results linked to climate scenarios are not being conducted. Therefore, this study predicted current and future potential habitats for the Republic of Korea reptiles, analyzed overlapping areas with protected sites, and calculated the SPI. Furthermore, we compared SPI values between ecologically disruptive species and general species. We also adapted the selection of Species Conservation Targets (SCT) for SPI value determination to the Republic of Korea context and compared these with existing assessment values. The results of this study suggest the necessity not only for additional quantitative expansion of protected areas but also for selecting new protected areas considering climate change. Furthermore, it enables a quantitative examination of the risk of invasive species penetrating protected areas due to climate change.

Materials and Methods

Research target species

The number of biological species (native species) in the Republic of Korea is estimated to be approximately 100,000 (Ministry of Environment, 2012), and as of 2023, 60,010 species are recorded and managed in the National Species List (National Biodiversity Center, 2023). Among these, 36 reptile species are recorded (National Institute of Biological Resources, 2024). Out of these 36 species, 32 species were selected as research subjects, excluding four endangered wild species. The excluded endangered species are one Class I species (black headed snake [*Sibynophis chinensis*]) and three Class II species (Korean rat snake [*Elaphe schrenckii*], Korean tiger lizard [*Eremias argus*], and Reeves's pond turtle [*Mauremys reevesii*]). As ectotherms, reptiles are highly susceptible to the impacts of global warming, and habitats exceeding the physiological optimal temperatures for some reptile species have already been observed (Biber *et al.*, 2023). This suggests reptiles may be more vulnerable to global warming than other taxonomic groups adapted to colder environments (Diele-Viegas & Rocha, 2018). Therefore, research to develop reptile conservation strategies under climate change impacts is urgently needed. The target species for this study were selected as reptile species for which location survey points from at least 50 points were available for applying species distribution models (SDM) (Coudun & Gégout, 2007; Franklin, 2009). Furthermore, all marine reptile species were excluded.

Predicting potential habitats under climate change

The most critical element in species conservation index assessment is identifying the species' habitat. To predict the potential habitat of reptiles under climate change, SDM were utilized. SDM is a tool that analyzes the relationship between species survey location data and environmental variables such as climate, topography, and soil to predict the potential habitat of the species (Schimper, 1903; Grinnell, 1904; Franklin, 2009). SDM is applied in diverse fields including biodiversity assessment, species resource and habitat management/restoration, protected area selection, and impact assessments of invasive alien species and climate change (Miller *et al.*, 2004; Peters & Herrick, 2004; Franklin, 2009; Thorn *et al.*, 2009; Shin *et al.*, 2015).

Environmental variables for predicting future potential habitats of reptiles were constructed by categorizing them into climatic and geographic factors (Shin *et al.*, 2024). Climatic variables utilized current (2000-2019) and future (2021-2100) data from the Korea Meteorological Administration (Korea Meteorological Administration, 2023). 19 bioclimate variables (Bioclim) were generated using current and future maximum temperature, minimum temperature, and precipitation data. Bioclim is known to be a key variable determining the distribution and habitat of animals, plants, and ecosystems (Araújo *et al.*, 2005; Attorre *et al.*, 2007). The Korea Meteorological Administration selected four types of Shared Socioeconomic Pathways (SSP) (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) as the national climate change standard scenarios (Korea Meteorological Administration, 2023). This study selected the intermediate pathway (SSP2-4.5) and the most severe pathway (SSP5-8.5). Geographic variables included elevation (Digital Elevation Model), slope, Topographic Wetness Index, and distance from inland water bodies (Shin *et al.*, 2024). Variables for the final SDM were selected by excluding highly correlated variables through Pearson's r correlation analysis and referencing prior studies (Koo *et al.*, 2015; Park *et al.*, 2017; Shin *et al.*, 2018).

Reptile locations for SDM were identified through 8 survey projects conducted by the National Institute of Ecology from 2013 to 2021: ("The National Ecosystem Survey," "Basic Survey on Inland Wetlands," "Ecosystem survey of Baekdudaegan Protected Area," "Natural Environment Survey of Specific Areas," "Ecological and Landscape Conservation Area Detailed Survey," "Specific Island Discovery Survey," "Specific Island Detailed Survey," "National Coastal Sand Dune Natural Environment Survey"), and data from the Korea National Park Service's "National Park Biological Resources Status Survey" conducted from 2002 to 2022 (Shin *et al.*, 2024).

To reduce the uncertainty of SDM, an ensemble model was applied in this study. Recently, ensemble models, which combine multiple model algorithms, have been utilized to mitigate the uncertainty arising from a single SDM approach (Thuiller *et al.*, 2009; Kwon, 2014; Shin *et al.* 2018). 10 SDM algorithms (Generalized Linear Model [GLM], Generalized Boosted Model [GBM], Generalized Additive Model [GAM], Classification Tree Model [CTA], Artificial Neural Network [ANN], Surface Range Envelope [SRE], Flexible Discriminant Analysis [FDA], Random Forest [RF], Multivariable Adaptive Regression Splines [MARS], Maximum Entropy [MaxEnt]) were used to predict the distribution of individual reptile species using an ensemble model approach, where the model validation values were weighted and combined (Allouche *et al.*, 2006; Koo *et al.*, 2017; Shin *et al.* 2018).

SDM accuracy was measured using the area under the curve (AUC) value of the receiver operating characteristic curve via 10-fold cross-validation (Shin *et al.*, 2018). The AUC value ranges from 0.5 to 1.0, and prediction accuracy is classified as follows: AUC 0.9-1.0, excellent; 0.8-0.9, good; 0.7-0.8, fair; 0.6-0.7, poor; 0.5-0.6, fail (Swets, 1988; Parker-Allie *et al.*, 2009). The potential habitat for individual reptile species predicted via SDM is estimated as a probability value. The predicted probability values for individual reptile species were classified into occupied areas (presence) and unoccupied areas (absence) (Shin *et al.*, 2018). The cutoff value for habitat/non-habitat classification was set at the point where the sum of the model's sensitivity and specificity was maximized (Liu *et al.*, 2005).

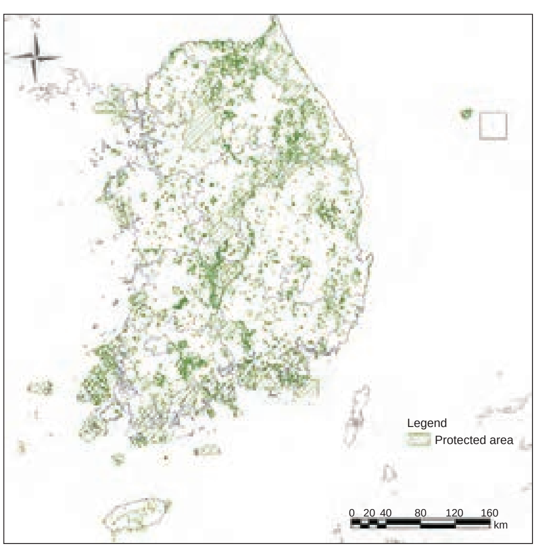

Fig. 1. Current status of protected areas in the Republic of Korea. Adapted from Korea Database on Protected Areas; 2024.

Assessment of the Species Protection Index

The SPI is an indicator developed by Group on Earth Observations Biodiversity Observation Network (GEO BON) in 2016, focusing on assessing how protected areas contribute to biodiversity conservation (Kim *et al.*, 2024). SPI is a tool that can promote the designation of protected areas for species' actual habitats and measure the resulting conservation outcomes (Jetz *et al.*, 2022). SPI can be assessed in six steps as follows (Jetz *et al.*, 2022; Kim *et al.*, 2024). (Step 1) Calculate the habitat area for each species within the target taxon or group, (Step 2) Calculate the overlap area between individual species habitats and protected areas, (Step 3) Calculate the SCT, (Step 4) Calculate the Species Protection Score (SPS) for each species, (Step 5) Assign weights to each species, (Step 6) Sum the weighted SPS to evaluate the final SPI.

This study conducted the following six steps to evalu-

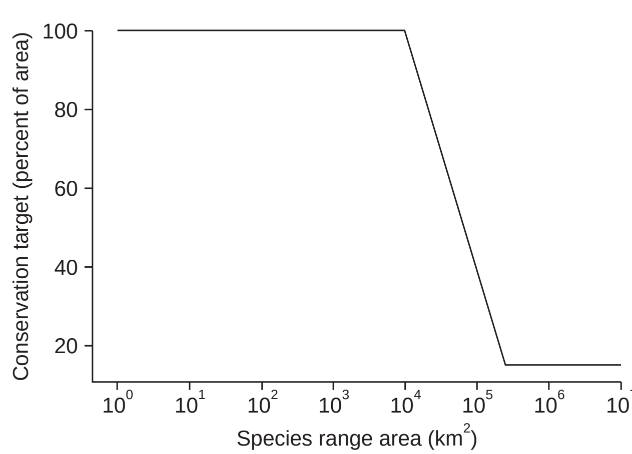

Fig. 2. The relationship between range of species and area-based conservation targets. Data from the article of Kim *et al.* (*Korean Journal of Ecology and Environment*, 57, 189-197).

ate the SPI. (Step 1) The habitat area for each reptile species (both current and future) was predicted using SDM. (Step 2) The overlapping area between the predicted individual reptile habitats and protected areas was calculated. Protected area data were obtained from the Korea Database on Protected Areas (Fig. 1; Korea Database on Protected Areas, 2024). (Step 3) The SCT value is determined based on the calculated individual habitat area of the reptile species. SCT represents the proportion of a species' habitat area within a country that should be protected. SCT is set at 100% for species with a habitat area under 10,000 km^2, and at 15% for species with a habitat area of 250,000 km^2 or more. Values in between are determined using a log-linear function (Fig. 2; Kim *et al.*, 2024). To maintain international comparability, we report SPI using the global SCT rule (100% at <10,000 km^2 to 15% at ≥250,000 km^2). In addition, we provide a country-specific sensitivity analysis (SCT-KR) that sets the 100% lower bound at 1,000 km^2 to reflect the Republic of Korea's small national extent and the prevalence of small-range species at national scales. (Step 4) SPS is calculated as the ratio of the species' habitat protection rate (the overlap between protected areas and the species' habitat) to the SCT value (Eq. 1). (Step 5) This study did not assign weights. However, weights could be assigned to species requiring urgent protection, such as endemic or endangered species within the country (Environmental Performance Index, 2024). (Step 6) This study averaged the SPS values of individual reptile species to derive the final SPI value.

$$Species\ Protection\ Score\ (SPS) = \frac{Area\ of\ habitat\ protected\ \left(\frac{Intersection\ area\ between\ protected\ areas\ and\ habitats}{Species\ habitat\ range}\right)}{Species\ consevation\ target\ (SCT)} \times 100 \quad \text{(Eq.1)}$$

To aid interpretation of SPI changes under climate scenarios, we additionally computed, for each species and time slice, (1) the total habitat area predicted by the

Table 1. Results of reptile Species Protection Index (SPI) assessment using species distribution models (current)

Scientific name	Habitat area (km^2)	Intersection area (km^2)	Species conservation target (%)		Protected area (%)	Species Protection Score	
			Original baseline	Revised baseline		Original baseline	Revised baseline
	(A)	(B)	(C)	(D)	(E)	{(E)/(C)}×100	{(E)/(D)}×100
Amphiesma vibakari	10,768.48	3,369.69	97.92	63.37	31.29	31.96	49.38
Dinodon rufozonatum	19,383.96	3,237.17	82.40	54.33	16.70	20.27	30.74
Elaphe dione	25,172.08	4,831.65	75.49	50.31	19.19	25.43	38.16
Hierophis spinalis	4,013.51	1,018.21	100.00	78.56	25.37	25.37	32.29
Oocatochus rufodorsatus	21,008.52	2,755.05	80.27	53.09	13.11	16.34	24.70
Rhabdophis tigrinus	37,487.76	5,416.87	64.98	44.18	14.45	22.24	32.71
Takydromus amurensis	26,281.18	6,723.26	74.36	49.64	25.58	34.40	51.53
Takydromus wolteri	22,687.81	3,022.77	78.24	51.90	13.32	17.03	25.67
Scincella huanrenensis	1,000.02	445.56	100.00	99.95	44.56	44.56	44.58
Scincella vandenburghi	23,387.13	4,381.49	77.44	51.44	18.73	24.19	36.42
Gloydius brevicaudus	16,578.15	3,170.20	86.52	56.73	19.12	22.10	33.71
Gloydius saxatilis	6,093.94	2,446.69	100.00	72.14	40.15	40.15	55.66
Gloydius ussuriensis	30,336.19	6,674.83	70.57	47.43	22.00	31.18	46.39
Pseudemys concinna	11,434.76	1,401.02	96.33	62.45	12.25	12.72	19.62
Pseudemys nelsoni	6,441.49	719.28	100.00	71.28	11.17	11.17	15.67
Trachemys scripta	15,920.42	1,513.49	87.59	57.36	9.51	10.85	16.57
Pelodiscus maackii	11,607.66	1,725.47	95.94	62.22	14.86	15.49	23.89
Pelodiscus sinensis	5,745.09	626.28	100.00	73.04	10.90	10.90	14.92
SPI (Overall mean across all species)						26.74	36.62
SPI (Overall mean across all species excluding ecosystem-disturbing [invasive] species)						28.16	38.53

*Ecosystem-disturbing (invasive) species.

SDMs and (2) the fraction of that area overlapping protected areas. These summaries are provided in Tables 1-4 to show how habitat-area trajectories and protected-area (PA)-overlap trajectories jointly determine SPS and, in turn, aggregate to the national SPI under each scenario.

Results

Selection of study species

Location data were collected for 32 reptile species inhabiting the Republic of Korea, excluding endangered species (four species). Among these 32 species, 18 species suitable for application to SDM were finally selected as study subjects (Table 5). The selected 18 species include three species designated as ecosystem-disturbing (invasive) species in the Republic of Korea. The three included species are the river cooter (*Pseudemys concinna*), Florida red-bellied cooter (*Pseudemys nelsoni*), and red-eared slider turtle (*Trachemys scripta*). The final SPI calculation was performed separately: one considering all 18 species including the ecosystem-disturbing species, and another excluding the three ecosystem-disturbing species (Table 5).

Predicted potential habitats under climate change

For the environmental variables in SDM to predict reptile potential habitats, nine variables (Bio03, Bio04, Bio05, Bio13, Bio17, digital elevation model [DEM], Slope, Topographic Wetness Index [TWI], D_water) were selected from 19 Bioclim variables and four topography-related variables, considering their correlations (Table 6; Shin *et al.*, 2024). The final ensemble model accuracy ranged from a minimum of 0.869 to a maximum of 0.999,

Table 2. Environmental variables used in the species distribution models

Category	Variable	Variables description (unit)
Climate	Bio03	Isothermality (mean diurnal range/ temperature annual range)×100 (%)
	Bio04	Temperature seasonality (standard deviation×100)
	Bio05	Max temperature of warmest month (°C)
	Bio13	Precipitation of wettest month (mm)
	Bio17	Precipitation of driest quarter (mm)
Geography	DEM	Digital elevation model (altitude; m)
	Slope	Slope calculated from DEM (°)
	TWI	Topographic Wetness Index calculated from DEM (unitless)
	D_water	Distance from inland water (m)

Table 3. Rankings of environmental variable importance for 18 species

Scientific name	Bio03	Bio04	Bio05	Bio13	Bio17	DEM	Slope	TWI	D_water
Amphiesma vibakari	7	5	2	8	1	3	4	9	6
Dinodon rufozonatum	9	1	4	7	3	6	5	8	2
Elaphe dione	9	3	1	8	5	6	7	4	2
Hierophis spinalis	6	2	1	3	5	4	9	7	8
Oocatochus rufodorsatus	6	4	8	7	5	1	9	2	3
Rhabdophis tigrinus	7	2	6	8	4	5	9	3	1
Takydromus amurensis	8	7	1	9	5	4	2	6	3
Takydromus wolteri	7	1	3	5	8	2	9	4	6
Scincella huanrenensis	6	7	1	8	4	2	9	5	3
Scincella vandenburghi	5	2	4	8	3	7	1	9	6
Gloydius brevicaudus	6	2	5	4	1	7	9	8	3
Gloydius saxatilis	4	7	1	8	2	3	5	6	9
Gloydius ussuriensis	8	3	1	9	4	2	7	6	5
Pseudemys concinna	2	4	5	3	8	1	9	6	7
Pseudemys nelsoni	3	2	1	7	8	4	9	6	5
Trachemys scripta	6	1	3	4	5	2	9	8	7
Pelodiscus maackii	4	9	8	5	6	2	7	1	3
Pelodiscus sinensis	6	1	3	2	7	4	9	5	8

DEM, digital elevation model; TWI, Topographic Wetness Index.
*Ecosystem-disturbing (invasive) species.

Table 4. Results of reptile habitat area (km^2) assessment using SDM: Current (2010) and SSP2-4.5 scenario (2020-2090)

Scientific name	2010	2020	2030	2040	2050	2060	2070	2080	2090
Amphiesma vibakari	10,768.48	10,403.12	8,865.98	10,965.35	10,733.22	13,346.92	11,372.53	6,702.55	6,238.58
Dinodon rufozonatum	19,383.96	18,509.20	15,277.36	14,813.59	20,976.97	24,405.49	22,374.94	23,322.51	21,662.03
Elaphe dione	25,172.08	24,913.64	27,316.94	30,201.40	30,726.47	36,984.37	35,390.98	30,395.41	29,601.76
Hierophis spinalis	4,013.51	3,298.57	3,027.37	2,381.07	2,278.54	2,344.35	2,152.86	2,356.56	2,253.09
Oocatochus rufodorsatus	21,008.52	13,604.87	4,117.19	1,305.80	1,558.45	951.09	507.87	1,297.01	605.97
Rhabdophis tigrinus	37,487.76	34,877.00	31,393.01	29,046.41	29,689.16	31,203.16	27,362.44	27,649.75	28,438.51
Takydromus amurensis	26,281.18	20,540.93	14,959.86	14,373.24	11,357.87	10,251.72	8,600.98	6,245.57	4,917.11
Takydromus wolteri	22,687.81	23,143.03	18,787.31	18,728.84	23,650.45	27,649.62	27,102.07	26,159.65	24,033.25
Scincella huanrenensis	1,000.02	349.64	1,947.26	2,055.65	28.19	21.37	28.16	15.55	21.37
Scincella vandenburghi	23,387.13	24,826.29	24,150.38	30,184.48	34,337.80	40,397.83	39,173.77	29,670.98	27,644.57
Gloydius brevicaudus	16,578.15	21,074.63	32,615.60	38,859.77	41,798.34	50,228.70	48,693.01	40,774.65	38,650.80
Gloydius saxatilis	6,093.94	5,915.16	6,472.01	8,563.03	9,631.22	12,513.86	12,198.70	10,070.10	9,558.15
Gloydius ussuriensis	30,336.19	23,096.57	14,011.24	12,464.94	11,791.14	11,167.37	8,785.78	6,654.43	5,447.64
Pseudemys concinna	11,434.76	26,179.02	28,634.31	19,297.71	15,617.68	10,545.04	8,228.89	8,053.93	6,107.88
Pseudemys nelsoni	6,441.49	18,903.71	35,741.08	45,241.18	46,368.73	47,355.90	45,726.31	44,082.83	33,145.02
Trachemys scripta	15,920.42	30,711.69	47,702.36	48,668.97	45,892.22	34,797.94	27,705.94	28,520.50	20,407.38
Pelodiscus maackii	11,607.66	11,172.77	5,876.91	3,098.61	3,530.43	2,983.95	1,985.38	2,528.75	1,783.96
Pelodiscus sinensis	5,745.09	4,326.06	2,611.56	1,424.15	2,697.70	2,947.14	3,009.20	4,336.57	3,403.67

SDM, species distribution model; SSP, Shared Socioeconomic Pathway.
*Ecosystem-disturbing (invasive) species.

Table 5. Results of reptile habitat area (km^2) assessment using SDM: Current (2010) and SSP5-8.5 scenario (2020-2090)

Scientific name	2010	2020	2030	2040	2050	2060	2070	2080	2090
Amphiesma vibakari	10,768.48	11,328.39	6,928.27	6,492.68	13,138.51	16,408.51	28,310.55	20,892.78	7,576.12
Dinodon rufozonatum	19,383.96	17,735.75	24,100.15	23,384.64	24,150.33	28,202.66	25,878.43	21,665.18	17,048.31
Elaphe dione	25,172.08	24,571.46	28,867.48	29,248.76	35,565.54	40,705.94	49,900.41	47,107.58	34,535.96
Hierophis spinalis	4,013.51	2,971.38	3,705.27	2,922.78	2,743.30	3,517.14	3,004.04	1,895.94	1,344.03
Oocatochus rufodorsatus	21,008.52	9,880.41	10,631.02	5,266.18	975.38	429.29	7.00	3.99	39.23
Rhabdophis tigrinus	37,487.76	33,119.59	33,626.49	32,078.85	32,162.42	34,156.98	35,401.11	34,424.98	30,272.89
Takydromus amurensis	26,281.18	19,829.18	11,872.78	9,597.37	10,690.00	8,227.24	6,904.57	4,330.83	1,724.03
Takydromus wolteri	22,687.81	23,253.41	25,497.81	24,766.88	27,933.29	32,749.49	33,722.12	28,556.46	19,795.22
Scincella huanrenensis	1,000.02	489.38	66.10	34.99	20.41	9.71	11.66	18.47	19.44
Scincella vandenburghi	23,387.13	25,792.16	21,912.56	23,879.51	39,992.46	47,041.45	59,911.46	56,325.22	32,386.43
Gloydius brevicaudus	16,578.15	18,950.56	29,719.40	34,106.45	44,806.18	51,479.73	62,957.28	64,608.31	55,124.73
Gloydius saxatilis	6,093.94	4,848.30	7,358.11	7,983.66	11,016.37	16,371.67	18,833.51	18,374.67	15,348.42
Gloydius ussuriensis	30,336.19	21,624.92	13,544.06	10,392.72	11,207.52	9,053.84	6,785.32	3,131.89	1,212.87
Pseudemys concinna	11,434.76	28,735.03	27,682.93	17,566.75	9,655.00	5,399.17	2,660.96	1,873.26	1,447.30
Pseudemys nelsoni	6,441.49	23,952.57	34,562.69	42,015.57	45,539.51	26,033.26	10,902.82	6,289.67	3,342.56
Trachemys scripta	15,920.42	34,444.94	53,316.90	50,087.60	33,909.12	17,813.40	8,015.41	4,050.35	2,909.95
Pelodiscus maackii	11,607.66	8,163.68	9,346.81	5,112.30	2,396.70	2,067.62	835.37	731.28	1,198.46
Pelodiscus sinensis	5,745.09	3,433.49	5,710.58	4,900.42	2,610.56	2,729.23	1,266.68	1,548.02	2,991.87

SDM, species distribution model; SSP, Shared Socioeconomic Pathway.
*Ecosystem-disturbing (invasive) species.

with an average value of 0.965 (Fig. 3).

Across the 18 species, the most frequently first-ranked predictor (environmental variable) was Bio5 (maximum temperature of the warmest month) in seven species (*Elaphe dione, Hierophis spinalis, Takydromus amurensis, Scincella huanrenensis, Gloydius saxatilis, Gloydius ussuriensis, and Pseudemys nelsoni*) followed by Bio4 (temperature seasonality) in four species (*Dinodon rufozonatum, Takydromus wolteri, Trachemys scripta, and Pelodiscus sinensis*) and Bio17 (precipitation of the driest quarter) in two species (*Amphiesma vibakari and Gloydius brevicaudus*). DEM was the top predictor for two species (*Oocatochus rufodorsatus and Pseudemys concinna*) while single-species leaders were Slope for *Scincella vandenburghi*, TWI for *Pelodiscus maackii*, and D_water (distance to inland water) for *Rhabdophis tigrinus*. No species had Bio03 or Bio13 as the highest-ranked predictor (Table 7).

The area of current (Table 5) and future (two scenarios: SSP2-4.5, SSP5-8.5) habitats was calculated for 18 reptile species. Based on the current (2010) potential habitat, the species with the largest areas in the Republic of Korea were the tiger keelback (*Rhabdophis tigrinus*), the Ussuri mamushi (*Gloydius ussuriensis*), and the Amur grass lizard (*Takydromus amurensis*), in that order. The species with the smallest areas were the dwarf skink (*Scincella huanrenensis*), the slender racer (*Hierophis spinalis*), and the Chinese softshell turtle (*Pelodiscus sinensis*), in that order. The species with the largest overlap area (intersection area) between predicted potential habitat and protected areas were the Amur grass lizard (*Takydromus amurensis*), Ussuri mamushi (*Gloydius ussuriensis*), and the tiger keelback (*Rhabdophis tigrinus*), in that order. Conversely, the species with the smallest overlap areas were the dwarf skink (*Scincella huanrenensis*), Chinese softshell turtle (*Pelodiscus sinensis*), and Florida red-bellied cooter (*Pseudemys nelsoni*). A larger potential habitat area did not necessarily correspond to a larger overlap area with

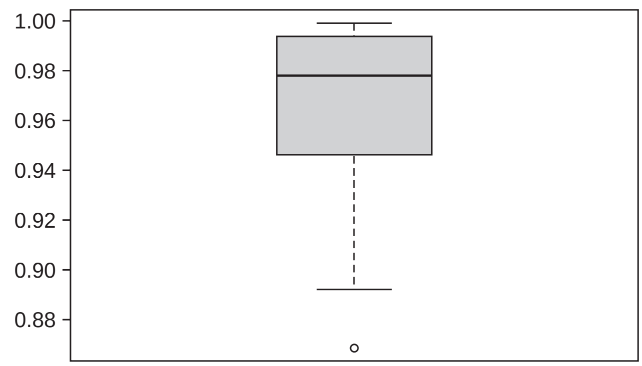

Fig. 3. Accuracy of the ensemble species distribution models.

Table 6. Proportion (%) of SDM-predicted habitat within protected areas: Current (2010) and SSP2-4.5 scenario (2020-2090)

Scientific name	2010	2020	2030	2040	2050	2060	2070	2080	2090
Amphiesma vibakari	31.29	29.45	30.37	29.73	30.12	29.23	30.26	32.15	31.68
Dinodon rufozonatum	16.70	16.30	17.40	17.92	16.12	15.57	15.89	15.21	15.26
Elaphe dione	19.19	19.00	18.69	18.99	18.24	17.32	17.71	18.13	18.30
Hierophis spinalis	25.37	23.36	22.25	23.39	24.32	24.96	25.03	23.69	23.78
Oocatochus rufodorsatus	13.11	15.15	19.88	21.98	20.71	20.30	21.91	19.21	23.63
Rhabdophis tigrinus	14.45	15.29	15.37	16.02	15.70	15.36	15.94	15.88	15.84
Takydromus amurensis	25.58	26.61	28.85	29.56	30.10	31.44	32.94	33.70	36.03
Takydromus wolteri	13.32	13.25	14.03	14.56	14.09	13.74	13.70	13.93	14.42
Scincella huanrenensis	44.56	52.42	17.43	16.02	52.32	58.20	47.67	76.75	59.84
Scincella vandenburghi	18.73	19.24	19.09	19.29	19.64	19.86	20.05	20.00	19.82
Gloydius brevicaudus	19.12	18.19	18.01	18.45	17.73	17.25	17.68	17.42	17.47
Gloydius saxatilis	40.15	39.47	39.06	36.48	33.39	31.58	33.06	32.68	32.44
Gloydius ussuriensis	22.00	23.21	25.30	26.63	28.37	29.93	31.23	32.24	33.49
Pseudemys concinna	12.25	10.37	13.95	15.56	16.39	17.09	18.42	18.83	19.34
Pseudemys nelsoni	11.17	9.11	10.14	10.58	11.31	12.27	13.53	13.59	15.01
Trachemys scripta	9.51	9.48	10.80	13.10	14.38	15.69	16.60	17.00	18.41
Pelodiscus maackii	14.86	17.93	21.39	23.43	22.50	21.45	23.70	23.17	26.98
Pelodiscus sinensis	10.90	12.61	14.96	18.64	13.42	12.59	11.89	11.92	12.70

SDM, species distribution model; SSP, Shared Socioeconomic Pathway.
*Ecosystem-disturbing (invasive) species.

Table 7. Proportion (%) of SDM-predicted habitat within protected areas: Current (2010) and SSP5-8.5 scenario (2020-2090)

Scientific name	2010	2020	2030	2040	2050	2060	2070	2080	2090
Amphiesma vibakari	31.29	28.43	28.59	30.36	28.86	26.97	23.37	25.14	27.84
Dinodon rufozonatum	16.70	16.12	14.78	15.09	15.45	14.83	15.58	16.39	17.01
Elaphe dione	19.19	18.57	17.78	17.68	17.29	16.49	16.27	16.71	18.28
Hierophis spinalis	25.37	24.33	20.89	21.53	23.72	22.84	24.08	26.85	28.18
Oocatochus rufodorsatus	13.11	15.84	15.31	15.71	20.40	20.35	24.33	25.22	30.73
Rhabdophis tigrinus	14.45	15.27	14.67	14.81	15.25	14.91	15.17	15.18	14.62
Takydromus amurensis	25.58	27.24	28.55	30.19	31.11	33.43	36.13	39.49	46.97
Takydromus wolteri	13.32	13.22	13.13	13.31	13.32	13.29	13.57	13.91	14.54
Scincella huanrenensis	44.56	37.26	50.89	56.84	62.97	81.66	54.65	45.54	44.27
Scincella vandenburghi	18.73	19.21	19.88	20.05	19.36	19.10	19.11	19.34	21.39
Gloydius brevicaudus	19.12	18.15	16.21	16.66	17.15	17.06	17.71	18.31	19.24
Gloydius saxatilis	40.15	43.18	32.73	32.58	32.25	28.91	31.41	32.98	35.73
Gloydius ussuriensis	22.00	23.51	24.50	26.30	29.51	32.46	36.23	44.13	54.21
Pseudemys concinna	12.25	10.77	14.70	15.79	17.08	18.27	25.00	34.73	43.48
Pseudemys nelsoni	11.17	9.40	10.85	11.28	12.45	15.22	15.72	17.24	23.79
Trachemys scripta	9.51	9.47	11.49	14.01	15.83	17.65	18.88	26.05	35.97
Pelodiscus maackii	14.86	19.34	18.82	19.95	22.27	22.69	32.16	34.56	30.73
Pelodiscus sinensis	10.90	12.51	13.46	13.72	14.68	14.34	12.52	14.37	14.33

SDM, species distribution model; SSP, Shared Socioeconomic Pathway.
*Ecosystem-disturbing (invasive) species.

protected areas.

Assessment of the Species Protection Index results

The species with the highest ratio of protected area to potential habitat area (intersection area between potential habitat and protected areas) based on current standards were the dwarf skink (*Scincella huanrenensis*), the Amur mamushi (*Gloydius saxatilis*), and the Asian keelback (*Amphiesma vibakari*), in that order (Table 5). The species with the lowest ratios were the red-eared slider turtle (*Trachemys scripta*), Chinese softshell turtle (*Pelodiscus sinensis*), Florida red-bellied cooter (*Pseudemys riori*), and river cooter (*Pseudemys concinna*), in that order. The overlap rate between habitats of species designated as ecosystem-disturbing species and protected areas was low. Furthermore, a high potential habitat area did not necessarily correlate with a high overlap rate with protected areas. The dwarf skink (*Scincella huanrenensis*) had the smallest potential habitat area yet exhibited the highest overlap rate with protected areas.

The current SPI score considering all species is 26.74 points, while the SPI score excluding ecosystem-disturbing species is 28.16 points. The SPI score adjusted to the Republic of Korea context based on SCT criteria is 36.62 points when considering all species and 38.53 points when excluding disturbance species. The SPI score was higher in all cases when ecosystem-disturbing species were excluded. The species with the highest SPS values were the dwarf skink (*Scincella huanrenensis*), the Amur mamushi (*Gloydius saxatilis*), and the Amur grass lizard (*Takydromus amurensis*), in that order. When the SCT criteria were modified to suit the Republic of Korea conditions, the ranking changed to the Amur mamushi (*Gloydius saxatilis*), the Amur grass lizard (*Takydromus amurensis*), and the Asian keelback (*Amphiesma vibakari*). The SPS values for the three ecosystem-disturbing species remained the lowest under both SCT methods.

Under the future SSP2-4.5 scenario, the SPI value excluding ecosystem-disturbing species remained lower than the current value (28.16) until 2070, then showed an increasing trend after 2080 (Fig. 4; Appendix 1). In the future SSP5-8.5 scenario, the SPI value excluding ecosystem-disturbing species also remained lower than the current value until 2050, then showed an increasing trend after 2060 (Fig. 5; Appendix 2). Both scenarios indicate that the SPI value decreases in the near future but increases in the more distant future.

The future trend of the SPI score, adjusted to reflect the Republic of Korea conditions based on the SCT standard, is as follows. Even in this case, when examining SPI values excluding ecosystem-disturbing species relative to the baseline, the SSP2-4.5 scenario showed lower SPI values than the current baseline value (38.53) (Fig. 4; Appendix 3). For the SSP5-8.5 scenario, values remained low until 2050 but showed a tendency to increase after 2060 (Fig. 5; Appendix 4). The SSP5-8.5 scenario exhibited similar trends regardless of whether the SCT criteria were modified or not.

The results of SPI value changes under future climate change scenarios, distinguishing between ecosystem-disturbing (invasive) species and non-disturbing (non-invasive) species, are as follows. Under the SSP2-4.5 scenario, the SPI values for ecosystem-disturbing species were significantly lower in the initial period (2010–2030), but the gap narrowed after 2040 (Figs. 4, 5). The SSP5-8.5 scenario also showed a similar pattern to the SSP2-4.5 scenario: a large gap in SPI values between ecosystem-disturbing species and non-disturbing species during the initial period (2010-2030), which sharply decreased by 2040. After 2090, the SPI values of ecosystem-disturbing species tended to exceed those of non-disturbing species. This suggests that ecosystem-disturbing species could rapidly infiltrate protected areas due to climate change.

Decomposition into (1) total predicted habitat area (Tables 1, 2) and (2) the proportion within protected areas (Tables 3, 4) shows that late-century SPI increases arise from higher PA representation despite range loss. For example, *Takydromus amurensis* declines in area (2010→2090: 26,281.18→4,917.11 km^2 under SSP2-4.5; 26,281.18→1,724.03 km^2 under SSP5-8.5), while its PA proportion rises (SSP2-4.5: 25.58→36.03%; SSP5-8.5: 25.58→46.97%). *Gloydius ussuriensis* exhibits a similar pattern, with area declines coupled with strong increases in PA proportion (SSP2-4.5: 22.00→33.49%; SSP5-8.5: 22.00→54.21%). These patterns are consistent with upslope/poleward shifts and spatial concentration of suitable climates into the Republic of Korea's mountainous PA.

Discussion

Our findings point to a consistent hierarchy of ecological controls rather than a single dominant driver of reptile suitability under warming. Thermal regimes—maximum

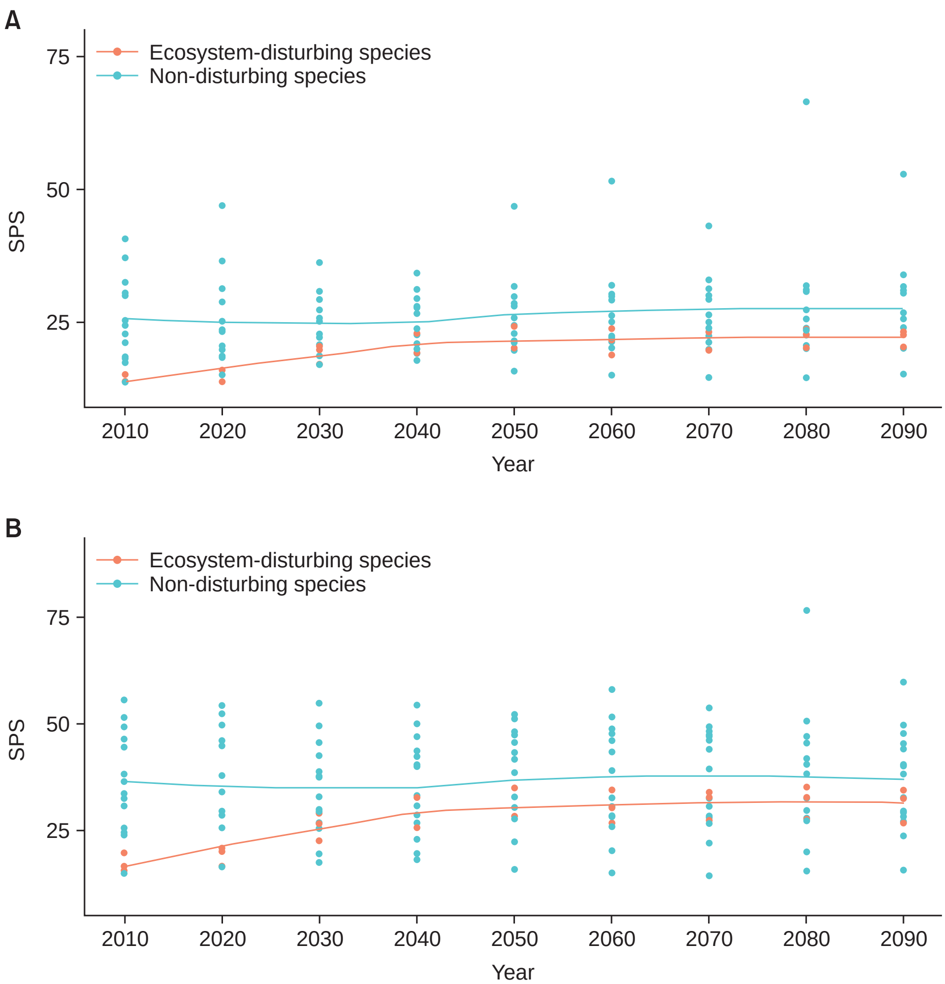

Fig. 4. Results of reptile SPS assessment using species distribution models (SSP2-4.5 scenario): (A) original baseline conservation target, (B) revised baseline conservation target. SPS, Species Protection Score; SSP, Shared Socioeconomic Pathway.

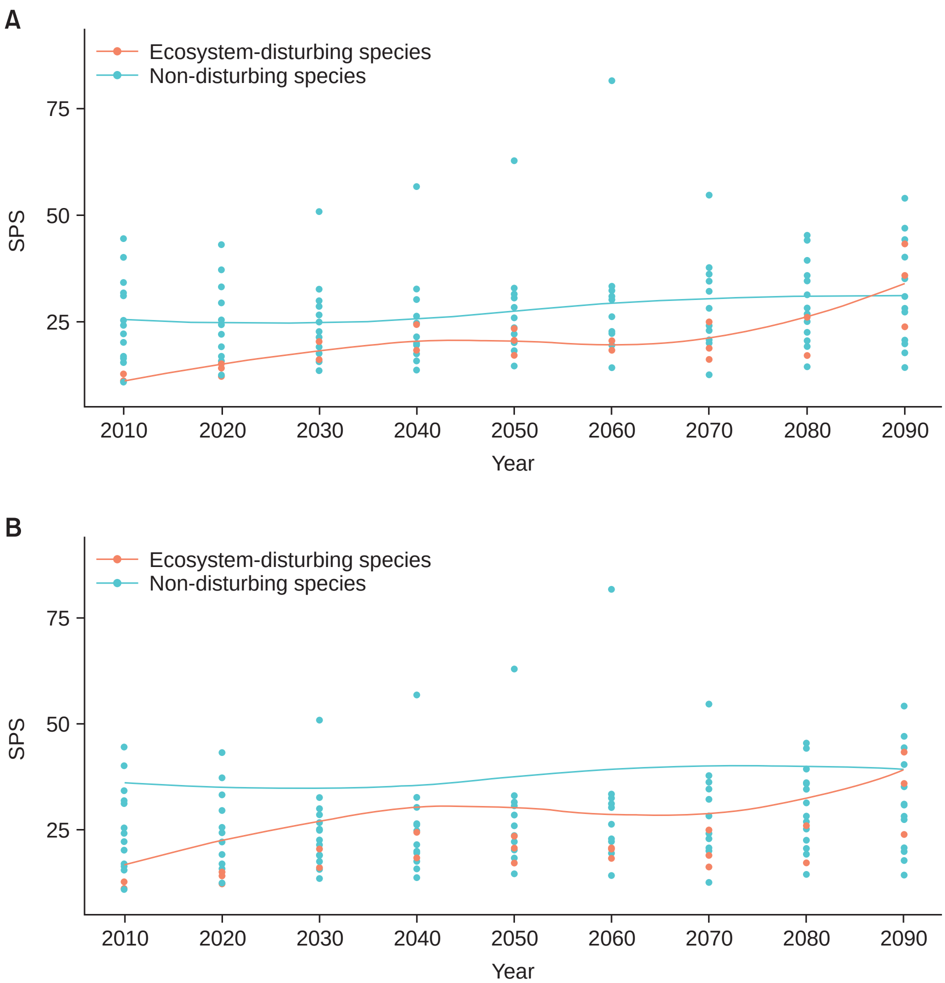

Fig. 5. Results of reptile SPS assessment using species distribution models (SSP5-8.5 scenario): (A) original baseline conservation target, (B) revised baseline conservation target. SPS, Species Protection Score; SSP, Shared Socioeconomic Pathway.

temperature of the warmest month (Bio5) and temperature seasonality (Bio4)—recurrently constrain lacertids (Lacertidae) and pit vipers (Crotalinae), consistent with theory and observations that climate warming tightens thermal safety margins and reshapes activity budgets and distributional limits in ectotherms (Sunday *et al.*, 2014; Chen *et al.*, 2011; Pecl *et al.*, 2017). In semi-aquatic taxa, hydrological and moisture variables (Topographic Wetness Index, distance to inland water, precipitation of the driest quarter) exert the greatest influence, underscoring the buffering and corridor functions of riparian and wetland systems as rainfall regimes are reconfigured. Topography (DEM, slope) consistently provides a second-tier variable importance, highlighting the role of elevational gradients and micro-refugia in enabling short-distance climate tracking (Jones *et al.*, 2016; IPCC, 2022). Interpreting suitability through this lens favors conservation strategies that pair lowland vulnerability management with reinforcement of elevational belts, microtopography, and riparian connectivity.

An apparent late-century rebound of SPI is best read as a change in representation, not as a wholesale improvement in habitat quantity or risk. Two non-exclusive mechanisms likely operate: (1) upslope/poleward displacement of suitable climates toward the mountain-biased PA network in the Republic of Korea, and (2) contraction with spatial concentration, whereby the remnants of suitability are disproportionately captured inside or adjacent to existing PAs. These processes are consistent with observed and predicted redistribution dynamics under rapid warming and with the configuration of the national PA portfolio (Chen *et al.*, 2011; Sunday *et al.*, 2014; Jones *et al.*, 2016). To prevent misinterpretation, we decomposed, for each species and time slice, total suitable area and the fraction overlapping PAs, allowing SPS/SPI trajectories to be interpreted as joint outcomes of area change and PA capture rather than as proxies for reduced extinction risk.

Rising representation within PAs should therefore not be equated with improved conservation status. Korea-specific pressures—rapid urbanization, dense road networks and fragmentation, coastal reclamation, and riparian modification—can degrade habitat quality inside and around PAs and constrain dispersal to emerging climates (Do *et al.*, 2022). Ecosystem-disturbing (invasive) reptiles may further exploit warmer conditions and linear infrastructure to establish along riverine and coastal corridors that intersect PA boundaries, emphasizing the need for biosecurity, early detection–rapid response, and targeted management at PA interfaces (IPCC, 2022; Pecl *et al.*, 2017). Because SPI measures representation rather than impact, parallel indicators (e.g., invasive incidence within PAs) should be tracked to ensure that rising SPI for invasives is not misread as a positive outcome.

Positioning SPI within policy frameworks requires balancing international comparability with national relevance. As a GBF Target 3 component indicator reported annually by Map of Life (Jetz *et al.*, 2022; Kim *et al.*, 2024), SPI should be presented using the published log-linear SCT rule (<10,000 km^2→100%; ≥250,000 km^2→15%) to maintain interoperability. At the same time, a clearly labeled sensitivity analysis using the Republic of Korea-adjusted lower bound (e.g., 1,000 km^2) can better reflect small national extent and the prevalence of small-range species in domestic planning. Dual reporting—global-rule SPI for GBF alignment and context-tuned SPI for national siting and management—avoids conflation while informing decisions at both scales (Jetz *et al.*, 2022; Kim *et al.*, 2024).

Uncertainties and limitations deserve explicit treatment. Ensemble SDMs mitigate but do not remove sensitivity to algorithm choice, thresholds, and global climate model (GCM)/SSP selection; these propagate into SPI and warrant uncertainty bands and multi-GCM aggregation (Franklin, 2009; Thuiller *et al.*, 2009; Koo *et al.*, 2017). We did not apply species weights nor include endangered taxa, limiting comparability with some global assessments; future work should evaluate weighting schemes that elevate endemics and threatened species (Block *et al.*, 2024; Jetz *et al.*, 2022). Moreover, dynamic land-use/land-cover change and explicit connectivity metrics were not yet integrated, despite their central roles in realized distributions and PA overlap; combining these with SDM suitability and continuing updates with national survey data will sharpen inference and policy salience (Miller *et al.*, 2004; Peters & Herrick, 2004; Shin *et al.*, 2024).

Taken together, the SPI framework—interpreted through the paired lenses of range trajectories and PA capture—offers a decision-ready measure of where protection most effectively represents climate-suitable habitats for reptiles as conditions warm. Delivering on the 30% target will depend not only on area expansion but on climate-informed configuration: securing elevational gradients and micro-refugia, reinforcing riparian/wetland connectivity, and institutionalizing invasive-species management at PA edges. In this role, SPI complements area-based goals by directing limited conservation effort to places where representation gains—and thus the prospects for persistence—are likely to be greatest (IPCC, 2022; Jones *et al.*, 2016; Kim *et al.*, 2024).

Conclusion

This study constructed ensemble SDM models for 18 reptile species (average AUC 0.965) and calculated SPI based on protected area representativeness to evaluate changes under different climate change scenarios. The current SPI was 26.74 for all species and 28.16 excluding ecosystem-disturbing species. Adjusting the SCT lower limit to 1,000 km^2 to reflect the Republic of Korea conditions increased these values to 36.62 and 38.53, respectively. Both scenarios (SSP2-4.5, SSP5-8.5) showed declines in the mid-term but recovery and increases in the late term. Ecosystem-disturbing species are likely to surpass general species in the long term, highlighting the importance of managing their penetration within protected areas. This suggests that a large potential habitat area does not necessarily equate to a high protection rate, indicating that the key is not how much is protected but where. However, limitations such as excluding endangered species, not applying weights, and not integrating connectivity, land-use change, and uncertainty may cause differences from international comparative values. Policy-wise, achieving the protected area expansion target (30%) alongside precise relocation to reptile core habitats, enhanced connectivity, proactive management of ecosystem-disturbing species, dual reporting under the Republic of Korea and international standards, and quantification of priority weighting and uncertainty are expected to increase the SPI's utility in decision-making. Furthermore, integrating with other taxonomic groups and refining the assessment procedures in the future is expected to further enhance the reliability of its policy utility.

Author Contributions

Conceptualization: MSS, SRK. Data curation: MSS, BRK. Formal analysis: MSS. Funding acquisition: MSS, SRK. Investigation: MSS, BRK. Methodology: MSS, BRK, SRK. Project administration: SRK. Resources: MSS, BRK, SRK. Software: MSS. Supervision: SRK. Validation: MSS, SRK. Visualization: MSS, BRK. Writing – original draft: MSS. Writing – review & editing: BRK.

Conflict of Interest

The authors declare that they have no competing interests.

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Appendix 1. Results of reptile SPS and SPI assessment using species distribution models (SSP2-4.5 scenario; Original baseline conservation target)

Scientific name	2020	2030	2040	2050	2060	2070	2080	2090
Amphiesma vibakari	29.79	30.37	30.51	30.73	31.68	31.36	32.15	31.68
Dinodon rufozonatum	19.49	19.62	20.03	20.08	20.41	20.21	19.62	19.21
Elaphe dione	25.08	25.49	26.86	25.97	26.50	26.64	25.71	25.70
Hierophis spinalis	23.36	22.25	23.39	24.32	24.96	25.03	23.69	23.78
Oocatochus rufodorsatus	16.51	19.88	21.98	20.71	20.30	21.91	19.21	23.63
Rhabdophis tigrinus	22.87	22.07	22.34	22.06	22.00	21.75	21.74	21.92
Takydromus amurensis	32.91	32.33	32.74	31.19	31.68	32.94	33.70	36.03
Takydromus wolteri	17.05	16.86	17.48	18.26	18.81	18.63	18.70	18.80
Scincella huanrenensis	52.42	17.43	16.02	52.32	58.20	47.67	76.75	59.84
Scincella vandenburghi	25.36	24.92	27.29	29.19	31.52	31.42	28.11	27.14
Gloydius brevicaudus	22.69	26.24	28.81	28.56	30.14	30.44	27.76	27.23
Gloydius saxatilis	39.47	39.06	36.48	33.39	33.61	34.94	32.78	32.44
Gloydius ussuriensis	29.84	27.82	28.32	29.70	30.87	31.23	32.24	33.49
Pseudemys concinna	13.93	19.36	18.85	18.61	17.35	18.42	18.83	19.34
Pseudemys nelsoni	10.96	15.31	17.63	19.05	20.87	22.65	22.39	22.00
Trachemys scripta	13.49	18.43	22.55	24.12	23.43	22.75	23.55	22.72
Pelodiscus maackii	18.50	21.39	23.43	22.50	21.45	23.70	23.17	26.98
Pelodiscus sinensis	12.61	14.96	18.64	13.42	12.59	11.89	11.92	12.70
SPI (Overall mean across all species)	23.69	22.99	24.08	25.79	26.47	26.31	27.33	26.92
SPI (Overall mean across all species excluding ecosystem-disturbing [invasive] species)	25.86	24.05	24.95	26.83	27.65	27.32	28.48	28.04

SPS, Species Protection Score; SPI, Species Protection Index; SSP, Shared Socioeconomic Pathway.
*Ecosystem-disturbing (invasive) species.

Appendix 2. Results of reptile SPS and SPI assessment using species distribution models (SSP5-8.5 scenario; Original baseline conservation target)

Scientific name	2020	2030	2040	2050	2060	2070	2080	2090
Amphiesma vibakari	29.44	28.59	30.36	31.15	31.07	32.28	31.27	27.84
Dinodon rufozonatum	19.03	19.28	19.49	20.18	20.46	20.84	20.63	19.82
Elaphe dione	24.39	24.74	24.72	26.05	26.26	28.34	28.35	27.23
Hierophis spinalis	24.33	20.89	21.53	23.72	22.84	24.08	26.85	28.18
Oocatochus rufodorsatus	15.84	15.58	15.71	20.40	20.35	24.33	25.22	30.73
Rhabdophis tigrinus	22.37	21.63	21.44	22.09	22.11	22.82	22.58	20.70
Takydromus amurensis	33.30	29.94	30.19	31.71	33.43	36.13	39.49	46.97
Takydromus wolteri	17.04	17.46	17.53	18.30	19.38	20.02	19.27	17.77
Scincella huanrenensis	37.26	50.89	56.84	62.97	81.66	54.65	45.54	44.27
Scincella vandenburghi	25.67	25.11	26.08	30.60	32.39	36.34	35.66	31.07
Gloydius brevicaudus	21.87	22.79	24.69	28.45	30.15	34.53	36.18	35.12
Gloydius saxatilis	43.18	32.73	32.58	33.14	33.29	37.77	39.36	40.35
Gloydius ussuriensis	29.57	26.67	26.61	30.47	32.46	36.23	44.13	54.21
Pseudemys concinna	14.96	20.15	18.57	17.08	18.27	25.00	34.73	43.48
Pseudemys nelsoni	12.24	16.17	18.21	20.80	20.40	16.11	17.24	23.79
Trachemys scripta	14.09	20.63	24.45	23.41	20.86	18.88	26.05	35.97
Pelodiscus maackii	19.34	18.82	19.95	22.27	22.69	32.16	34.56	30.73
Pelodiscus sinensis	12.51	13.46	13.72	14.68	14.34	12.52	14.37	14.33
SPI (Overall mean across all species)	23.14	23.64	24.59	26.53	27.91	28.50	30.08	31.81
SPI (Overall mean across all species excluding ecosystem-disturbing [invasive] species)	25.01	24.57	25.43	27.75	29.53	30.20	30.90	31.29

SPS, Species Protection Score; SPI, Species Protection Index; SSP, Shared Socioeconomic Pathway.
*Ecosystem-disturbing (invasive) species.

Appendix 3. Results of reptile SPS and SPI assessment using species distribution models (SSP2-4.5 scenario; Revised baseline conservation target)

Scientific name	2020	2030	2040	2050	2060	2070	2080	2090
Amphiesma vibakari	46.08	45.76	47.13	47.49	48.66	48.39	45.50	44.14
Dinodon rufozonatum	29.61	30.00	30.66	30.36	30.66	30.48	29.54	29.01
Elaphe dione	37.65	38.11	39.97	38.61	39.01	39.30	38.24	38.28
Hierophis spinalis	28.64	26.83	27.00	27.87	28.74	28.40	27.30	27.20
Oocatochus rufodorsatus	25.34	25.43	22.94	22.24	20.30	21.91	20.02	23.63
Rhabdophis tigrinus	33.77	32.77	33.30	32.86	32.69	32.52	32.49	32.72
Takydromus amurensis	49.80	49.47	50.17	48.12	49.02	49.29	46.96	47.77
Takydromus wolteri	25.68	25.60	26.55	27.48	28.11	27.87	28.02	28.27
Scincella huanrenensis	52.42	19.43	18.02	52.32	58.20	47.67	76.75	59.84
Scincella vandenburghi	38.08	37.47	40.61	43.15	46.15	46.09	41.87	40.56
Gloydius brevicaudus	34.30	38.89	42.28	41.72	43.49	44.03	40.62	39.97
Gloydius saxatilis	54.37	54.86	54.52	51.29	51.71	53.80	50.74	49.75
Gloydius ussuriensis	44.95	42.66	43.57	45.77	47.65	46.96	45.55	45.35
Pseudemys concinna	20.87	28.88	28.60	28.43	26.82	27.28	27.75	26.82
Pseudemys nelsoni	16.64	22.58	25.63	27.64	30.25	32.91	32.60	32.57
Trachemys scripta	20.06	26.69	32.61	35.03	34.61	34.00	35.14	34.39
Pelodiscus maackii	28.55	29.43	28.39	27.93	25.81	26.52	27.04	29.64
Pelodiscus sinensis	16.29	17.57	19.72	15.84	15.11	14.33	15.41	15.66
SPI (Overall mean across all species)	33.51	32.91	33.98	35.79	36.50	36.21	36.75	35.87
SPI (Overall mean across all species excluding ecosystem-disturbing [invasive] species)	36.37	34.29	34.99	36.87	37.69	37.17	37.74	36.79

SPS, Species Protection Score; SPI, Species Protection Index; SSP, Shared Socioeconomic Pathway.
*Ecosystem-disturbing (invasive) species.

Appendix 4. Results of reptile SPS and SPI assessment using species distribution models (SSP5-8.5 scenario; Revised baseline conservation target)

Scientific name	2020	2030	2040	2050	2060	2070	2080	2090
Amphiesma vibakari	45.42	40.75	42.66	47.86	47.40	48.18	47.29	40.47
Dinodon rufozonatum	28.95	28.99	29.34	30.33	30.54	31.24	31.15	30.21
Elaphe dione	36.64	36.89	36.85	38.43	38.44	40.92	41.10	40.23
Hierophis spinalis	29.24	26.18	25.80	28.10	28.34	29.01	29.80	29.54
Oocatochus rufodorsatus	24.49	24.08	21.12	20.40	20.35	24.33	25.22	30.73
Rhabdophis tigrinus	33.13	32.00	31.81	32.77	32.69	33.68	33.37	30.80
Takydromus amurensis	50.46	46.14	46.34	49.01	49.52	51.45	51.02	51.29
Takydromus wolteri	25.66	26.19	26.32	27.34	28.72	29.62	28.75	26.93
Scincella huanrenensis	37.26	50.89	56.84	62.97	81.66	54.65	45.54	44.27
Scincella vandenburghi	38.47	37.91	39.22	44.83	46.96	51.72	51.01	46.06
Gloydius brevicaudus	33.20	33.94	36.51	41.38	43.43	48.92	51.13	50.32
Gloydius saxatilis	57.07	47.27	47.92	51.17	50.79	57.34	59.81	61.70
Gloydius ussuriensis	44.65	40.94	41.15	47.03	49.15	51.41	53.57	55.90
Pseudemys concinna	22.32	30.11	28.27	26.26	24.69	29.45	38.47	46.12
Pseudemys nelsoni	18.41	23.89	26.59	30.23	30.57	24.89	24.07	29.23
Trachemys scripta	20.82	29.64	35.28	34.63	31.73	27.80	33.22	43.08
Pelodiscus maackii	28.60	28.71	26.66	25.74	25.56	32.16	34.56	31.62
Pelodiscus sinensis	15.45	18.41	18.17	17.23	16.97	13.00	15.41	17.25
SPI (Overall mean across all species)	32.79	33.50	34.27	36.43	37.64	37.77	38.58	39.21
SPI (Overall mean across all species excluding ecosystem-disturbing [invasive] species)	35.25	34.62	35.11	37.64	39.37	39.84	39.92	39.15

SPS, Species Protection Score; SPI, Species Protection Index; SSP, Shared Socioeconomic Pathway.
*Ecosystem-disturbing (invasive) species.

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Contribution of Key Biodiversity Areas to Societal Challenges through Nature-based Solutions

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ABSTRACT

This research was conducted to determine how Key Biodiversity Areas (KBAs), areas that make a critical contribution to global biodiversity conservation, can contribute to solving societal challenges through Nature-based Solutions (NbS). To this end, a total of 21 documents, including international academic journals and institutional reports, were analyzed. Cases were classified and organized according to the seven major types of societal challenges defined by the International Union for Conservation of Nature NbS Global Standard. The analysis revealed that KBA-based NbS contributes most extensively in the 'environmental degradation and biodiversity loss' domain, aligning with the fundamental purpose of KBAs being biodiversity conservation. This was followed by contributions to water security, climate change mitigation and adaptation, and economic and social development. Conversely, case accumulation was limited in some areas, such as human health and food security, likely due to the relatively recent establishment of KBA standards. In terms of research scale, most studies were conducted at a global scale, while regionally, the most active NbS application was reported in Asia and Africa. This research demonstrates that KBAs can function as core spatial platforms for NbS implementation beyond simple protected areas. It also suggests that KBAs hold significant strategic value for achieving international environmental goals, such as the Kunming-Montreal Global Biodiversity Framework and the Sustainable Development Goals.

Keywords: Biodiversity conservation, Climate change, Key Biodiversity Areas, Nature-based Solutions, Societal and environmental challenges

Introduction

Climate change is having various impacts globally across society, including rising temperatures, sea level rise, more frequent and severe torrential rains, changes in precipitation patterns, and alterations in ocean currents. These changes significantly affect diverse sectors such as agriculture, public health, water use, energy production, and biodiversity (Rawat *et al*., 2024). Measures are needed to adapt to climate change and mitigate greenhouse gas emissions in order to reduce the damage caused by these changes and to positively impact health, biodiversity, food security, and other areas (Korea Meteorological Administration, 2024).

Nature-based Solutions (NbS) are gaining attention as an integrated solution to address complex environmental crises such as biodiversity loss and increased disasters. NbS are actions to protect, sustainably manage, and restore natural and modified ecosystems in ways that effectively and adaptively address societal challenges, providing both human well-being and biodiversity benefits (International

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Union for Conservation of Nature [IUCN], 2020). The recognized scope of societal challenges currently includes climate change (adaptation and mitigation), disaster risk reduction, ecosystem degradation and biodiversity loss, food security, human health, social and economic development, and water security. Importantly, while one or more societal challenges can be the entry point for NbS, the priority is to leverage the potential of NbS to provide multiple benefits, whereby one intervention addresses several challenges (IUCN, 2020).

Protected Areas can play an important role in climate change adaptation as NbS (Lipka *et al*., 2023). For example, Forests work to increase the minimum river low flow during droughts and to decrease the magnitude and pace of floods (Lipka *et al*., 2023). From this perspective, Key Biodiversity Areas (KBAs)—regions scientifically proven to hold high ecological value for biodiversity conservation—can be viewed as more than mere conservation zones. They serve as foundational areas for providing diverse ecosystem services such as carbon sequestration and disaster mitigation. Thus, KBAs represent crucial spatial units capable of maximizing the practical effectiveness of NbS.

KBA is a region that contributes significantly to the global conservation of biodiversity (Ahn & Kang, 2024), and the KBA standards were approved by the IUCN Council and launched at the 2016 World Conservation Congress in Hawaii (IUCN, 2022). As of 2025, 16,602 KBAs are registered worldwide (KBA homepage, 2025; November 1st), demonstrating their potential as a strategic foundation for applying NbS.

Additionally, NbS and KBA serve as indicators for fulfilling international commitments. NbS is utilized as a means to achieve Kunming-Montreal Global Biodiversity Framework (KMGBF) targets 8 (Minimize the Impacts of Climate Change on Biodiversity and Build Resilience) and 11 (Restore, Maintain and Enhance Nature's Contributions to People). Meanwhile, KBAs are also used as indicators for KMGBF 3 (Conserve 30% of Land, Waters and Seas), as well as indicators for UN Sustainable Development Goals (SDGs) 15 (Life on land). Thus, KBAs transcend simple conservation areas; they represent spatial units that can contribute to the implementation of various international environmental goals through the strategic application of NbS. However, to maximize the strategic value of KBA, it is necessary to conceptually clarify the mechanism by which KBA—as sites critical for global biodiversity conservation—translate their intrinsic ecological value into practical contributions across the seven major societal and environmental challenges addressed by NbS.

This relationship forms the core of the research question: In what ways does the established function of KBAs as sites of critical importance for global biodiversity contribute to solving the diverse societal challenges prioritised by the NbS framework? This research analyzes existing literature and case studies to examine how NbS implemented in KBAs can contribute to solving specific social challenges, thereby identifying the multidimensional value of KBAs.

Materials and Methods

Literature review

To ensure the relevance and specificity of the analyzed literature to the research's core objective (Contribution of KBAs to Societal Challenges through NbS), inclusion criteria were applied:

(1) Topical relevance: The document must explicitly discuss NbS and their contribution to at least one of the seven major societal challenges identified by the IUCN Global Standard

(2) Geographic/scope relevance: The document must explicitly address the implementation or contribution of NbS within a KBAs. Studies focusing only on general protected areas or non-KBA sites were excluded.

(3) Content focus: The document must present empirical data, case studies, or analytical assessments of the NbS contribution.

(4) The collected data from the identified literature were organized and analyzed based on the seven types of major societal challenges addressed by NbS. The seven major societal and environmental challenges identified in the IUCN Global Standard are: Climate change mitigation and adaptation; disaster risk reduction; economic and social development; human health; food security; water security; and environmental degradation and biodiversity loss (IUCN, 2020) (Table 1).

Results

Analysis of the 21 selected studies indicates that the societal challenge to which KBAs most frequently contribute is environmental degradation and biodiversity loss (Table 2) (Baumbach *et al*., 2023; Dong *et al*., 2024; Eken *et al*., 2004; Gacheru *et al*., 2023; Goyal *et al*., 2025; Kullberg *et al*., 2019; Lansley *et al*., 2025; Larsen *et al*., 2012; Máiz-Tomé *et al*., 2017; Mehlomakhulu & Buschke, 2023; Neugarten *et al*., 2014; 2018; Plumptre *et al*., 2019; 2024; 2025; Shrestha *et al*., 2021; Sun *et al*., 2022; Tognelli *et al*., 2017; Trew *et al*., 2024; Visconti *et al*., 2019; World Wide Fund for Nature, 2024). The next most frequently addressed areas are water security, followed by climate change mitigation and adaptation, economic and social development, disaster risk reduction, human health, and food security. Overall, these findings demonstrate that KBAs can function not only as sites for biodiversity conservation but also as strategic spatial units capable of contributing to the resolution of a wide range of major

Table 1. IUCN NbS Global Standard: seven major societal challenges

Major societal challenges	Role of NbS in addressing the challenge
1. Climate change mitigation and adaptation	Utilizing NbS to address climate change through three core functions: Ecosystem-based Mitigation by preventing the degradation and loss of natural ecosystems to avoid emissions; functioning as a 'natural carbon sink' through the conservation and restoration of forests, wetlands, and oceans; and enabling Ecosystem-based Adaptation and Ecosystem-based DRR (Eco-DRR) to help vulnerable communities increase their resilience to adverse climate effects
2. Disaster risk reduction (DRR)	Utilizing the regulatory role of ecosystem services (e.g., wetlands, forests, coastal systems) to cost-effectively reduce risks from natural hazards. NbS serves as protective barriers or buffers to decrease physical exposure, protect infrastructure, and support quicker livelihood recovery, forming the basis of the Eco-DRR approach
3. Economic and social development	Utilizing NbS to promote sustainable economic growth and social well-being by supporting nature-based livelihoods, job creation, and inclusive local development. NbS enhances community resilience and long-term socio-economic stability through the sustainable management of ecosystem services
4. Human health	Recognizing the natural environment's role as a determinant of human health, well-being, and social cohesion. NbS aims to utilize nature's benefits—such as improving environmental quality (heat, noise), promoting physical and social activity, and providing sources of medicines—to enhance physical and mental health outcomes
5. Food security	Achieving sustainable food systems through an ecosystem-aware approach. This involves leveraging NbS to protect wild genetic resources, manage wild species, and utilize stable ecosystem services to stabilize food availability and access during periods of environmental or political stress
6. Water security	Utilizing water-related services provided by 'natural infrastructure' (such as forests, wetlands, and floodplains) to address exacerbated water crises. The goal is to achieve sufficient and safe water management and preserve ecosystem function simultaneously
7. Environmental degradation and biodiversity loss	Utilizing conservation through protection, restoration, and sustainable use to maintain or enhance biodiversity, serving as a critical input to NbS, thereby reversing ecosystem degradation and biodiversity loss while providing simultaneous benefits to human well-being

IUCN, International Union for Conservation of Nature; NbS, Nature-based Solutions.

societal challenges.

The literature analysis indicates that most of the selected studies were conducted at a global scale (Eken *et al*., 2004; Kullberg *et al*., 2019; Lansley *et al*., 2025; Larsen *et al*., 2012; Neugarten *et al*., 2018; Plumptre *et al*., 2025; 2024; Sun *et al*., 2022; Trew *et al*., 2024; Visconti *et al*., 2019), followed by Africa (Gacheru *et al*., 2023; Mehlomakhulu & Buschke, 2023; Neugarten *et al*., 2018; Plumptre *et al*., 2019; World Wide Fund for Nature, 2024), Asia (Dong *et al*., 2024; Goyal *et al*., 2025; Shrestha *et al*., 2021), Europe (Máiz-Tomé *et al*., 2017), North America (Tognelli *et al*., 2017), and Central America (Baumbach *et al*., 2023).

Discussion

This research demonstrates that KBAs contribute to a wide range of societal and environmental challenges addressed through NbS, suggesting that KBAs have the capacity to function as strategic spatial units beyond their role in biodiversity conservation. The contributions observed in the environmental degradation and biodiversity loss reflect the fundamental ecological role of KBAs in sustaining species and habitats. As evidenced by Eken *et al*. (2004), Kullberg *et al*. (2019), and Plumptre *et al*. (2024), identifying and protecting KBAs represents one of the most effective approaches to preventing global biodiversity loss. For example, Baumbach *et al*. (2023) quantitatively demonstrated that protected areas within KBAs maintain higher biome stability than unprotected areas KBAs. These findings suggest that substantial policy-driven conservation efforts must accompany the identification process to effectively mitigate environmental degradation and biodiversity loss.

Table 2. Key contributions of NbS within KBAs to societal challenges

No	References	Key contribution	Seven major societal challenges						
			CC	DRR	ESD	HH	FS	WS	EDBL
1	Eken *et al*., 2004	KBAs as a means to reduce global biodiversity loss							O
2	Larsen *et al*., 2012	Substantial human well-being benefits from safeguarding KBAs	O		O			O	
3	Neugarten *et al*., 2014	Assessment of the ecosystem service values of KBAs in Madagascar	O	O	O	O	O	O	O
4	Máiz-Tomé *et al*., 2017	Freshwater KBAs for water and ecosystems in North-Western Mediterranean sub-region						O	O
5	Tognelli *et al*., 2017	Freshwater KBAs for water and ecosystems in Canada						O	O
6	Neugarten *et al*., 2018	Ecosystem service modeling in protected areas (incl. KBAs)	O	O					O
7	Kullberg *et al*., 2019	KBA protection increasing threatened species coverage							O
8	Plumptre *et al*., 2019	Mapping KBAs and critical conservation sites in Uganda							O
9	Visconti *et al*., 2019	Utilizing KBAs for conservation outcomes							O
10	Shrestha *et al*., 2021	KBAs provide a high degree of ecosystem services in Chindwin River Basin, Myanmar	O					O	
11	Sun *et al*., 2022	Global trade analysis for KBA and global biodiversity integrity							O
12	Baumbach *et al*., 2023	Protected KBAs have higher ecosystem stability							O
13	Gacheru *et al*., 2023	Status of Kenya's KBA and recommendations for enhancing various ecosystem services		O	O			O	O
14	Mehlomakhulu & Buschke, 2023	Built & natural capital in South African KBA tourism			O				
15	Dong *et al*., 2024	KBA conservation as a win-win for biodiversity and climate goals in China	O						O
16	Plumptre *et al*., 2024	Using KBAs to halt biodiversity loss & meet GBF goals							O
17	Trew *et al*., 2024	Tropical KBAs acting as climate refugia	O						O
18	World Wide Fund for Nature, 2024	How the Kenyan banking sector can protect KBAs			O				
19	Goyal *et al*., 2025	GIS mapping of ecosystem services and threats provides a scientific basis for conservation planning			O			O	O
20	Lansley *et al*., 2025	Bird sites offer co-benefits for other species and humans							O
21	Plumptre *et al*., 2025	KBA & systematic conservation planning-guided expansion achieves KMGBF Target 1 and halts biodiversity loss							O

NbS, Nature-based Solutions; KBAs, Key Biodiversity Areas; CC, climate change mitigation and adaptation; DRR, disaster risk reduction; ESD, economic and social development; HH, human health; FS, food security; WS, water security; EDBL, environmental degradation and biodiversity loss; GBF, Global Biodiversity Framework.

Protecting areas of high biodiversity, including KBAs, contributes to climate change mitigation by reducing CO_2 emissions through carbon storage and sequestration, while also supporting climate change adaptation (Gacheru *et al*., 2023; Larsen *et al*., 2012; Neugarten *et al*., 2018). In particular, Trew *et al*. (2024) show that tropical KBAs can function as climate refugia under changing temperature regimes. In addition, evidence from some KBAs demonstrates their contribution to disaster risk reduction through ecosystem functions such as flood regulation (Neugarten *et al*., 2018).

Beyond environmental benefits, KBAs have also been shown to support economic and social development, for example through ecotourism opportunities (Neugarten *et al*., 2018) and contributions to the maintenance of human cultural diversity (Larsen *et al*., 2012). Furthermore, studies on freshwater KBAs in the Mediterranean (Máiz-Tomé *et al*., 2017) and Canada (Tognelli *et al*., 2017) underscore the importance of defining geographic priorities for freshwater biodiversity conservation and managing these areas to secure adequate environmental flows necessary to sustain vulnerable freshwater ecosystems, thereby enhancing water security.

Case studies demonstrating the contribution of NbS within KBAs to addressing societal challenges were most frequently conducted at the global scale. However, when examined by region, a relatively larger number of studies were identified in Asia and Africa. This pattern may reflect the fact that KBA-related research has been particularly active in these regions, as well as that Asia and Africa contain extensive areas of high ecological value while simultaneously experiencing strong anthropogenic pressures such as development and land-use change (Goyal *et al*., 2025; Neugarten *et al*., 2018; Plumptre *et al*., 2019). Consequently, the need for NbS that can simultaneously support biodiversity conservation and address societal and environmental challenges may be especially pronounced in these regions.

This research has several limitations. First, the relatively small sample size (n=21) of the analyzed literature may limit the generalizability of the findings. In particular, contributions to human health and food security were not identified, with the exception of an analysis in Madagascar (Neugarten *et al*., 2018). This is likely due to the limited accumulation of research, given that the KBA standard was established relatively recently in 2016. Second, the literature selection criteria were restricted to documents explicitly mentioning 'KBA' and the 'seven major societal challenges' defined by the NbS Global Standard. Consequently, related studies using similar concepts or terminologies, such as 'green infrastructure' or 'ecosystem-based adaptation,' may have been excluded.

Despite these limitations, this research supports the hypothesis that KBAs provide a foundation for the application of NbS. Specifically, it suggests that KBAs can generate a wide range of societal benefits beyond conservation objectives and hold significant strategic value for advancing international environmental targets, including the KMGBF and the SDGs. To fully realize this potential, future research should quantitatively assess the multiple values of KBAs and strengthen their integration into policy frameworks and decision-making processes.

Author Contributions

Conceptualization: NA, SRK. Data curation: NA, YS. Formal analysis: NA. Funding acquisition: SRK. Investigation: NA, SC, BRK. Methodology: NA, SC, YS. Project administration: NA. Resources: NA, SC, BRK. Supervision: SRK. Writing – original draft: NA, SRK. Writing – review & editing: NA, SRK.

Conflict of Interest

The authors declare that they have no competing interests.

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Distribution Characteristics and Management of *Sicyos angulatus* Communities in Riparian Ecosystems of Korea

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ABSTRACT

This study aimed to investigate the long-term dynamics of *Sicyos angulatus* communities, an invasive alien vine that threatens riparian biodiversity in Korea, and to provide baseline information for effective management strategies. Field surveys were conducted annually from 2020 to 2024 at four sites along the Han and Nakdong Rivers. At each site, the distribution area, importance value, and Shannon–Wiener diversity index were measured. The distribution area of *S. angulatus* fluctuated across years and sites, with temporary decreases followed by renewed expansion at some locations. Regardless of area changes, the species consistently increased in importance within plant communities, while species diversity declined, indicating progressive simplification and homogenization of riparian vegetation. NMDS ordination confirmed these structural changes and revealed significant effects of both year and site on community composition, confirming that *S. angulatus* drives structural shifts across temporal and spatial scales. These findings indicate that the ecological impact of *S. angulatus* extends beyond spatial expansion, encompassing increased dominance and the degradation of native plant diversity and resilience. Therefore, management strategies should address not only the control of its spatial spread but also the restoration of community structure through integrated removal, revegetation, and monitoring efforts.

Keywords: Invasive speceis, Plant community, *Sicyos angulatus,* Species diversity

Introduction

An alien species is defined under the Act on the Conservation and Use of Biological Diversity (abbreviated as the Biological Diversity Act) as an organism that has been introduced intentionally or naturally from abroad and exists outside its original range or habitat (Ministry of Government Legislation, Republic of Korea, 2024). Among them, alien species that are considered to pose high potential risk or are already evaluated as highly hazardous and require management are designated and publicly notified under the same Act as Alert Alien Species, Ecosystem Disturbing Concern Species, and Ecosystem Disturbing Species. Ecosystem disturbing species are defined as organisms that disrupt or are likely to disrupt the balance of the ecosystem. As of October 2024, a total of 40 taxa, including one genus of the *Trachemys* turtles, 21 other animal species, and 18 plant species, have been designated and publicly announced (Ministry of Government Legislation, Republic of Korea, 2024).

Internationally, alien species that have become estab-

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lished and exert negative impacts on biodiversity and ecosystems are defined as invasive alien species (IAS). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Roy *et al.*, 2023) reports that IAS are one of the major drivers of global biodiversity loss. Consequently, countries around the world are making continuous efforts to manage and prevent their spread.

Sicyos angulatus L. (burcucumber) is an annual climbing herb of the family Cucurbitaceae, native to North America, and it primarily occurs along riverbanks and adjacent riparian areas (Kurokawa, 2009; Kurokawa *et al.*, 2009; Larché, 2004). Under non-competitive conditions, a single *S. angulatus* plant can produce approximately 4,500 to 78,000 seeds (Esbenshade *et al.*, 2001; Kurokawa, 2009; Smeda & Weller, 2001a), and germination can occur continuously throughout the growing season (Messersmith *et al.*, 1999). In Korea, germination mainly occurs from April to May but can continue successively until mid-September (Kang, 2014). It is presumed that *S. angulatus* was introduced into Korea during the late 1970s or 1980s, mixed with imported grains from North America. Furthermore, its spread is thought to have been facilitated in the late 1980s when it was used as a rootstock for cucurbit crops such as watermelon and cucumber (Kang, 2014; National Institute of Ecology [NIE], 2021). Owing to the high ecological risk it poses to natural ecosystems following its introduction into Korea, *S. angulatus* was designated and has been managed as an Ecosystem Disturbing Species since 2009.

In some invaded regions abroad, *S. angulatus* has caused economic damage, such as reducing crop yields in maize (*Zea mays*) fields (Dowler, 1994; Shimizu, 1999). In Japan in particular, it has spread into natural ecosystems, where it suppresses the growth of native plants and causes ecological damage (Watanabe *et al.*, 2002). Due to these impacts, *S. angulatus* has been included among the legally and institutionally regulated IAS in several countries. For example, in Japan, it is designated as a “Specified Invasive Alien Species” under the Invasive Alien Species Act, which prohibits its import, transport, possession, and cultivation (Ministry of the Environment, Japan, 2004). In the Catalonia region of Spain, *S. angulatus* is designated as a “quarantine pest,” and compulsory control measures are implemented to prevent its spread (Government of Catalonia, 2005). In parts of Italy, *S. angulatus* has been listed on the regional blacklist of IAS, with monitoring and control measures enforced to limit its spread (Regione Lombardia, 2019). Even in its native range, the United States, *S. angulatus* has been designated as a noxious weed in several states, including Delaware, as a measure to prevent agricultural losses (Delaware Department of Agriculture, 1986).

Thus, *S. angulatus* is recognized both in Korea and abroad as a representative invasive alien plant species that requires intensive management, and ecological studies tailored to different habitat types are essential for developing effective management strategies. In particular, riparian zones, the primary habitats of *S. angulatus*, exhibit high environmental variability and pronounced vegetation dynamics, highlighting the importance of understanding the species’ distribution patterns in these areas. Accordingly, ecological studies focusing on *S. angulatus* in riparian areas have also been conducted in Korea. For example, previous studies have examined various ecological aspects of *S. angulatus*, including the effects of environmental factors such as flow velocity and soil texture on its population density in rivers (Lee *et al.*, 2020), the impact of its invasion on riparian vegetation in Korea (Lee *et al.*, 2015), and changes in weed species composition within *S. angulatus* communities (Moon *et al.*, 2008). However, these previous studies have been limited to short-term surveys lasting 1 or 2 years, and research on long-term community structural dynamics remains scarce. Therefore, this study aims to analyze the structural and distributional changes of *S. angulatus* communities along riparian zones over a 5-year period, to elucidate its ecological impacts and distribution patterns, and to provide baseline information for establishing effective management strategies.

Materials and Methods

Study area

The study sites were selected as part of the “Monitoring of Invasive Alien Species” project conducted by the NIE. To investigate the distribution patterns of *S. angulatus* in

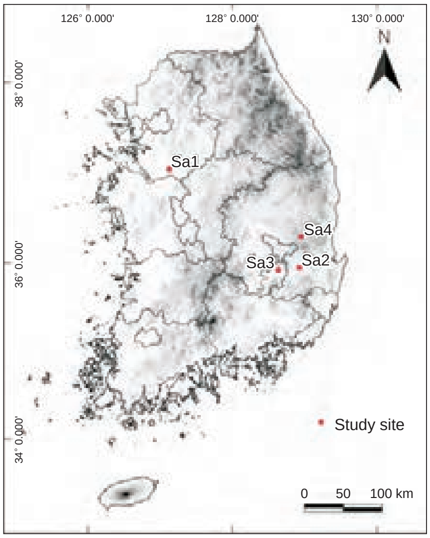

Fig. 1. Location of riparian monitoring sites for *Sicyos angulatus* communities surveyed from 2020 to 2024 in the Republic of Korea.

riparian areas, four sites characterized by riparian habitats were selected for analysis. The four study sites included one location in the Han River basin (Sa1) and three locations in the Nakdong River basin (Sa2-Sa4) (Fig. 1, Table 1).

The monthly average temperature (°C) and monthly precipitation (mm) recorded from 2019 to 2024 at the nearest automatic weather observation stations to each study site are shown in Fig. 2 (Korea Meteorological Administration, 2025).

Survey and analysis method

The four selected study sites were designated as fixed monitoring plots, and field surveys were conducted annually over a period of approximately 5 years, from 2020 to 2024. Field surveys were conducted between July and September, the period when *S. angulatus* reaches its peak

Table 1. Survey sites for *Sicyos angulatus* community monitoring

Site No.	Survey period	Location	Latitude	Longitude
Sa1	2020-2024	Oegacheon-ri, Wongok-myeon, Anseong-si, Gyeonggi-do	37.039121	127.126301
Sa2	2020-2024	Bongjuk-ri, Geumho-eup, Yeongcheon-si, Gyeongsangbuk-do	35.942718	128.922378
Sa3	2020-2024	Bongmu-dong, Dong-gu, Daegu	35.918249	128.632916
Sa4	2020-2024	Gameun-ri, Andeok-myeon, Cheongsong-gun, Gyeongsangbuk-do	36.2906791	128.9480369

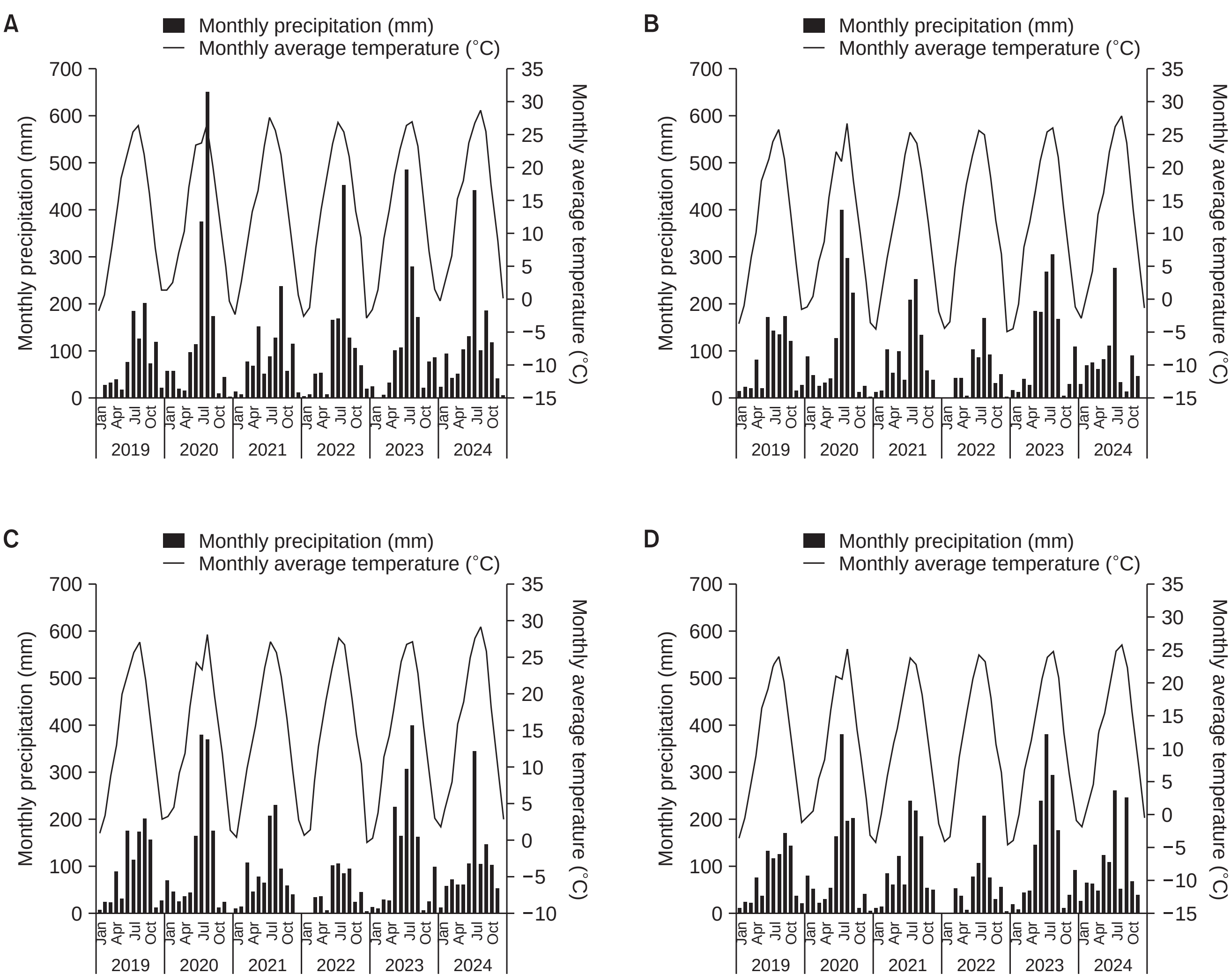

Fig. 2. Monthly average temperature (°C) and monthly precipitation (mm) at the study site. (A) Sa1, (B) Sa2, (C) Sa3, and (D) Sa4.

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growth.

To understand the competitive interactions and spread patterns of *S. angulatus* within the surrounding vegetation at each site, a current vegetation map was prepared. The same survey area was maintained as much as possible at each fixed site. However, due to the characteristics of the river environment and anthropogenic disturbances (e.g., river construction), the surveyed area varied slightly between years. To accurately assess the relative dominance of *S. angulatus* communities, the ratio of the *S. angulatus* community area to the total surveyed area was calculated and analyzed.

In addition, vegetation surveys were conducted in parallel to examine the distribution characteristics of *S. angulatus*. The vegetation survey was conducted using the quadrat method, recording the coverage of species occurring in each vegetation layer. At each study site, ten 1×1 m quadrats were randomly established within the entire area of the *S. angulatus* community for sampling. The coverage of each species was recorded using a nine-grade scale based on the modified Braun-Blanquet cover-abundance scale (Westhoff & van der Maarel, 1978). Based on the collected data, the importance value (IV) for each species was calculated as the mean of its relative coverage and relative frequency, in order to compare the relative dominance of the target species within the community. Using the IV, the Shannon-Wiener diversity index (Shannon, 1948) was calculated to evaluate annual changes in community diversity.

Statistical analysis

Annual variations in the Shannon-Wiener diversity index (H′) and IV of *S. angulatus* communities were tested for each study site from 2020 to 2024. Since the data were repeatedly measured at the same sites, a non-parametric repeated-measures test (Friedman test; Friedman, 1937) was conducted. When significant differences were found, pairwise Wilcoxon signed-rank tests were performed as post hoc analyses to identify specific differences between years (Wilcoxon, 1945). To correct for Type I errors arising from multiple comparisons, the Holm method was applied (Holm, 1979).

To examine changes in vegetation community structure, a non-metric multidimensional scaling (NMDS) analysis was performed (Kruskal, 1964). The NMDS was based on Bray–Curtis dissimilarity (Bray & Curtis, 1957) and reduced to two dimensions, and the analysis was conducted using the metaMDS function of the vegan package (Oksanen *et al*., 2025). The stress value was presented as an indicator to assess the goodness of fit of the community

Table 2. Annual change in the distribution area (%) of *Sicyos angulatus* from 2020 to 2024

Site no.	Year	Total vegetation area (m^2)	*Sicyos angulatus* area (m^2)	Area percentage (%)
Sa1	2020	30,366	18,955	62.5
	2021	23,295	2,682	11.5
	2022	26,982	1,915	7.1
	2023	8,674	5,668	65.3
	2024	27,446	11,696	42.6
Sa2	2020	18,442	8,516	46.2
	2021	18,481	984	5.3
	2022	18,481	9,017	49.3
	2023	18,481	4,944	26.8
	2024	18,480	4,901	26.5
Sa3	2020	11,701	8,028	68.6
	2021	10,090	2,985	29.6
	2022	10,090	4,116	40.8
	2023	10,090	2,838	28.1
	2024	10,092	2,577	25.5
Sa4	2020	13,175	2,743	20.8
	2021	13,202	658	5.0
	2022	13,202	2,146	16.3
	2023	13,202	2,047	15.5
	2024	13,203	2,109	16.0

structure. To examine differences among communities, permutational analysis of variance (PERMANOVA) was performed using the adonis2 function with 999 permutations (Anderson, 2001), and the homogeneity of multivariate dispersion among groups was tested using the betadisper function (Anderson *et al*., 2006; Warton *et al*., 2012).

All statistical analyses were performed using R version 4.4.1 (The R Foundation, Vienna, Austria; R Core Team, 2024), with a significance level set at $P<0.05$.

Results and Discussion

Temporal and spatial variation in *Sicyos angulatus* communities

Over the 5-year period, the proportion of the *S. angulatus* distribution area relative to the total vegetation area at each site exhibited a dynamic pattern, characterized by repeated increases and decreases (Table 2). In particular, site Sa1 showed the greatest fluctuation, with the distribution area sharply decreasing to 11.5% in 2021 and then increasing to 65.3% in 2023. Similarly, site Sa2 exhibited a sharp rebound, increasing from 5.3% in 2021 to 49.3% in 2022, indicating a high degree of community recovery resilience. At site Sa3, the distribution area decreased to 29.6% in 2021 and then increased again to 40.8% in 2022, showing a moderate level of fluctuation. In contrast, site Sa4 maintained a relatively stable proportion of approximately 15-20% throughout the 5-year period. These dynamic changes in *S. angulatus* communities are associated with the periodic disturbances in river ecosystems, and are likely to be strongly influenced by summer rainfall patterns. *S. angulatus* prefers humid, nutrient-rich riverine environments and possesses traits that favor seed dispersal by flooding and rapid recolonization of open niches created by the removal of competing vegetation (Uchida *et al*., 2012). Therefore, heavy rainfall events are considered decisive environmental factors that optimize the growth conditions of *S. angulatus*, enhance its early dominance, and consequently expand its community coverage.

The species diversity within *S. angulatus* communities showed a decreasing trend over time, whereas the IV of *S. angulatus* exhibited a continuous increase (Fig. 3). When the annual average changes were analyzed by combining all study sites, statistically significant differences were

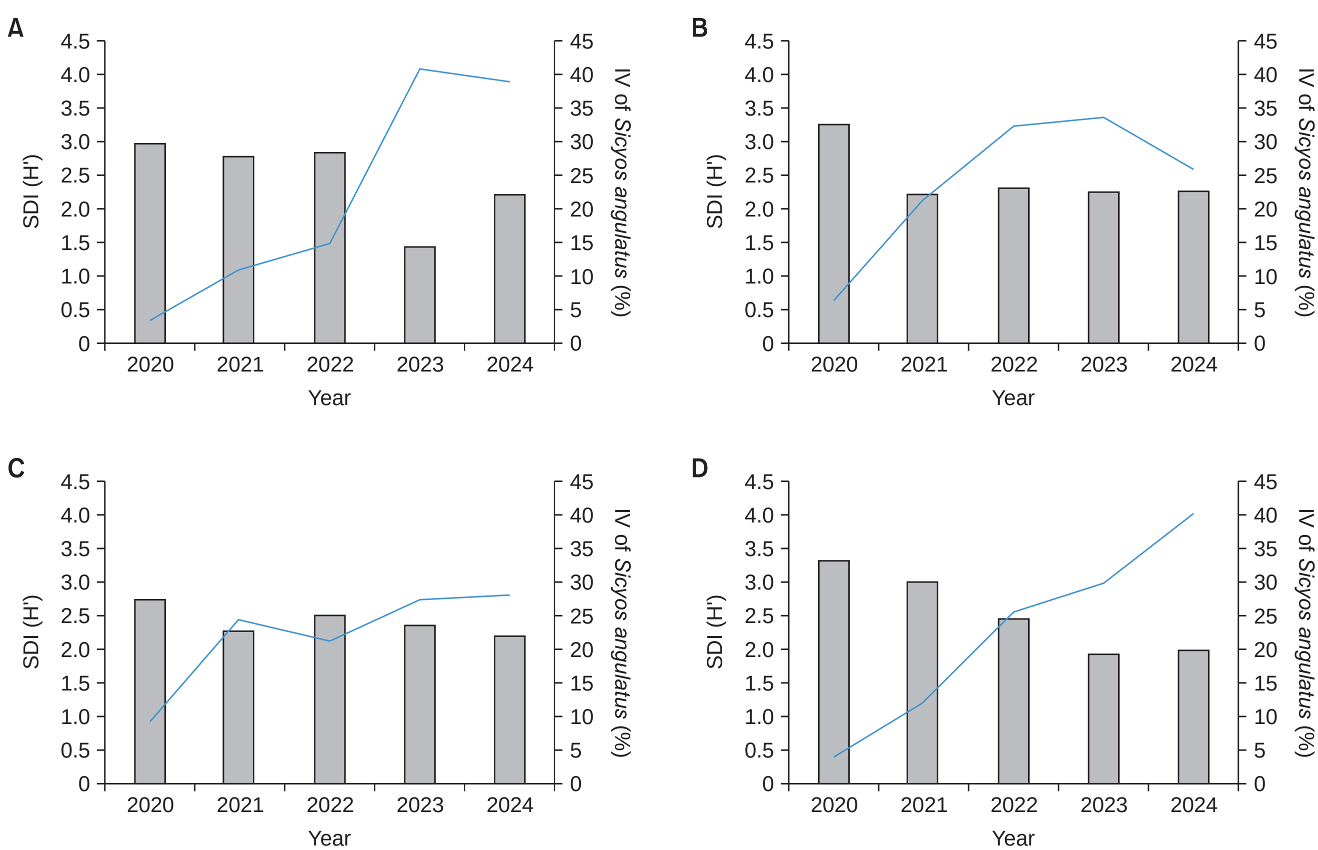


Fig. 3. Annual changes in SDI (H´, bar graph) and *Sicyos angulatus* IV (line graph) at each site: (A) Sa1, (B) Sa2, (C) Sa3, and (D) Sa4. SDI, Shannon-Wiener diversity index; IV, importance value.

observed overall (Friedman test, $P<0.05$) (Fig. 4). The species diversity index within the communities declined from 3.1 in 2020 to a minimum of 2.0 in 2023, indicating a progressive simplification of the community structure. In contrast, the IV of *S. angulatus* increased sharply from 5.6% in 2020 to 32.9% in 2023, confirming its intensified dominance. These results are consistent with previous studies reporting that the intensity of invasion negatively affects the species diversity of native vegetation (Valone & Weyers, 2019). As the dominance intensity of invasive species increases, the reduction in native plant diversity within the community becomes more pronounced (Valone & Weyers, 2019). In particular, *S. angulatus* effectively excludes competing plants by maximizing light interception and spatial occupation through its dense climbing growth form (Önen *et al*., 2015; Smeda & Weller, 2001b). However, the post hoc pairwise Wilcoxon test did not reveal any significant differences between specific year pairs. This is likely because the number of study sites was limited and the magnitude of annual variation was relatively small, making it difficult to achieve statistical significance in pairwise comparisons.

The NMDS analysis conducted to examine changes in the plant community structure within *S. angulatus* stands yielded a stress value of 0.212, indicating an acceptable level for interpreting the community structure. The community ordination showed partial separation both by year and by site (Fig. 5). In the annual analysis, the 2020 community was relatively distinct from those of other years, while the 2023 community also exhibited greater variability, indicating pronounced structural changes in specific years. Sites Sa1 and Sa4 showed relatively higher temporal variability in their distribution patterns compared to other sites, and particularly, Sa4 tended to form communities spatially separated from the others. These annual separations and increased variability in community structure are closely associated with the previously observed decline in species diversity and the intensified dominance of *S. angulatus* (Figs. 3, 4). In other words, the continuous spread and dominance of *S. angulatus* are interpreted to have simplified riparian plant communities over time and driven progressive homogenization of vegetation structure across sites (Valone & Weyers, 2019). The phenomenon whereby increased dominance of invasive species reduces spatial community diversity has been documented in several studies, and in frequently disturbed riparian environments, invasive species tend to rapidly reestablish after disturbance, thereby accelerating temporal and spatial homogenization of vegetation (Anderson *et al*., 2006; Warton *et al*., 2012). The relatively high interannual variability observed at Sa1 and Sa4 suggests that these sites experienced greater environmental disturbance or heterogeneity in the invasion process compared to the other sites. Therefore, the community separation patterns and high variability identified in the NMDS results are interpreted as reflecting transitional stages in which hydrological disturbances and the spread of invasive species jointly alter vegetation stability and species composition at each site.

PERMANOVA results revealed that both year ($R^2=0.048$, $P=0.001$) and site ($R^2=0.075$, $P=0.001$) had significant effects on the structure of plant communities. However, the test for homogeneity of multivariate dispersion indicated slight violations of the homogeneity assumption for both year and site groups ($P<0.05$). Thus, the significant PERMANOVA results likely reflect not only differences in species composition among groups but also the combined influence of community variability observed in the NMDS analysis.

Suggestions for management strategies

Based on the findings of this study, *S. angulatus* progressively reduced species diversity within its communities over the 5-year observation period, while its IV increased

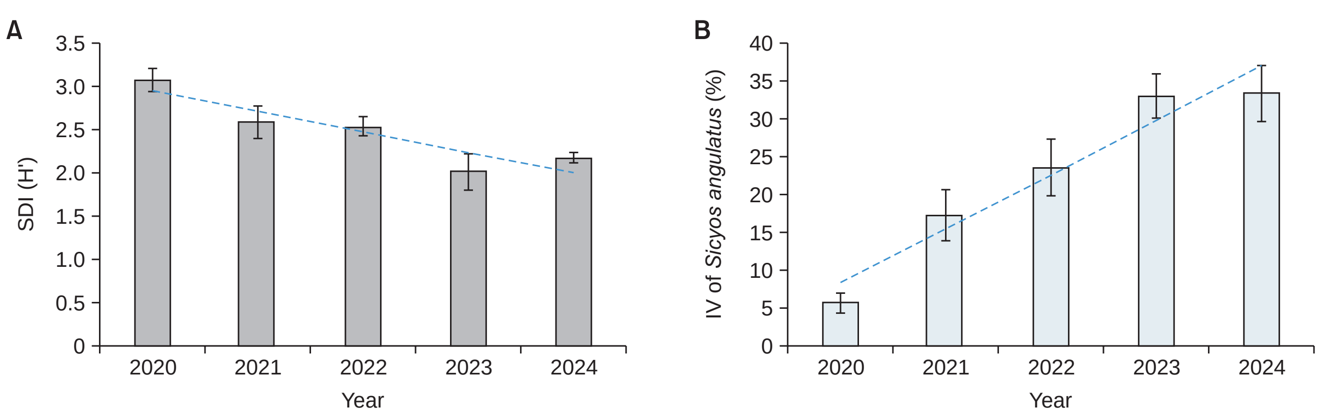
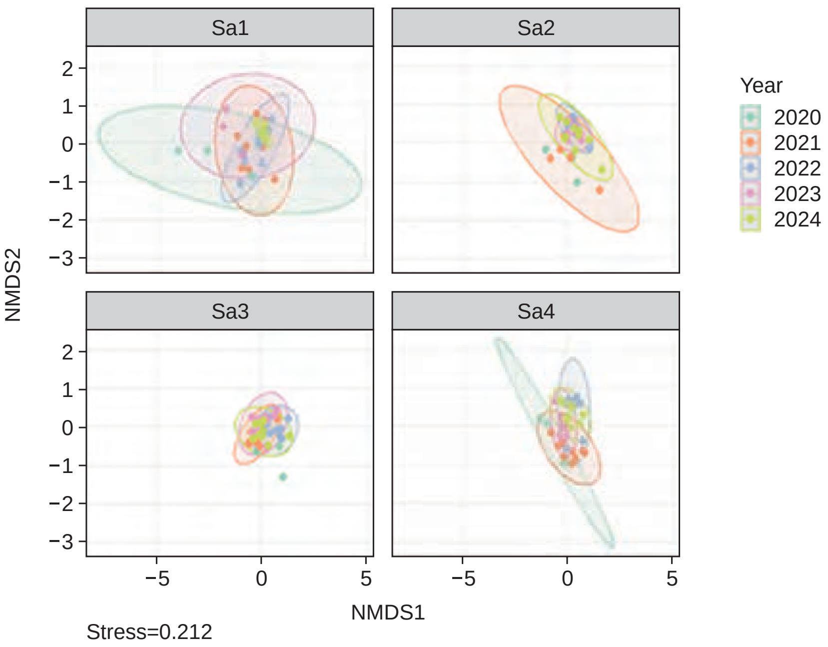


Fig. 4. Annual mean changes of (A) SDI (H′) and (B) *Sicyos angulatus* IV across the study sites ($P<0.05$). SDI, Shannon-Wiener diversity index; IV, importance value.

B



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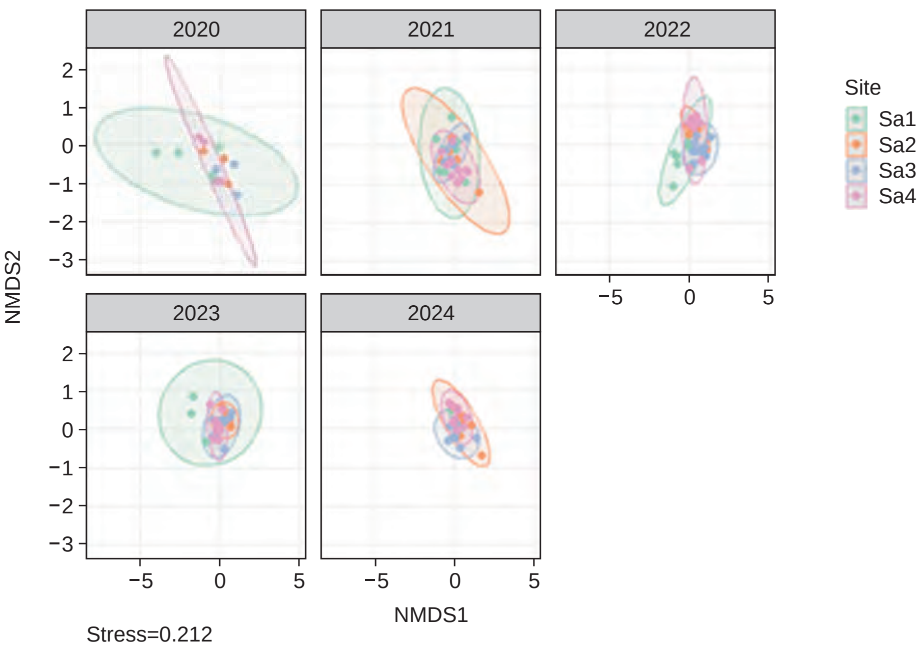

Fig. 5. NMDS ordination of plant communities by site (A) and year (B) (stress=0.212). PERMANOVA indicated significant differences in community composition among years (R^2=0.048, *P*=0.001) and sites (R^2=0.075, *P*=0.001). NMDS, non-metric multidimensional scaling.

sharply, indicating a progressive intensification of dominance within the community (Figs. 3, 4). These changes contributed to the simplification and spatial homogenization of vegetation structure over time, consistent with previous findings that higher invasion intensity leads to a pronounced decline in native plant diversity (Smeda & Weller, 2001a; Valone & Weyers, 2019). Furthermore, the year-specific community separation and high variability observed at sites Sa1 and Sa4 in the NMDS analysis suggest transitional stages of reduced vegetation stability, driven by the combined effects of disturbance intensity and invasive species expansion (Anderson *et al*., 2006; Warton *et al*., 2012). Taken together, the expansion of *S. angulatus* represents not merely an increase in alien species abundance, but an ecological threat capable of reducing the structural resilience of riparian plant communities. In particular, riparian ecosystems are highly vulnerable to disturbance and exhibit high reinvasion rates after removal (Richardson *et al*., 2007). Therefore, instead of relying solely on physical removal, an integrated management approach combining removal, restoration, and long-term monitoring is essential for sustainable control.

In this context, management efforts should be strategically designed to reflect the temporal and spatial dynamics revealed in this study. Rapid removal immediately after major rainfall or flooding events is critical, as these disturbances promote seed dispersal and rapid recolonization. Because germination in Korea mainly occurs from April to May and can continue until mid-September (Kang, 2014; Kurokawa, 2009; Messersmith *et al*., 1999; Smeda & Weller, 2001a), two to three follow-up removals throughout the growing season are recommended to prevent seed set and minimize seed-bank replenishment. Priority should be given to sites that exhibited high interannual variability or rebound patterns, such as Sa1 and Sa2, whereas relatively stable sites such as Sa4 can be monitored at a baseline level. To prevent reinvasion after removal, active revegetation with native riparian species possessing dense growth and strong rooting ability is essential to occupy open niches and stabilize the soil (NIE, 2021; Richardson *et al.*, 2007). In addition, management should aim for "zero seed set" by removing vines before flowering and fruiting, considering that each plant can produce thousands of seeds (Esbenshade *et al.*, 2001; Kurokawa, 2009; Smeda & Weller, 2001a). Regular monitoring of IV and H′ during the growing season (July-September) will help detect early reinvasion, and action thresholds (e.g., IV ≥30% or area coverage ≥30-40%) may be adopted to trigger intensified control (Valone & Weyers, 2019). Furthermore, coordinated management between upstream and downstream reaches should be implemented to suppress propagule flow, particularly after floods, since seed and plant fragments can easily disperse along water currents (Richardson *et al.*, 2007; Uchida *et al.*, 2012).

Author Contributions

Conceptualization: SIL. Data curation: HY, DC. Formal analysis: HY. Funding acquisition: SIL. Investigation: DC. Methodology: SIL. Resources: DC. Supervision: SIL. Visualization: HY. Writing – original draft: SIL. Writing – review & editing: SIL, HY, DC.

Conflict of Interest

The authors declare that they have no competing interests.

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Assessing the Risk of Spread of the Invasive Grasshopper *Melanoplus differentialis* via Soil and Debris Translocation in Ulsan, Korea

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ABSTRACT

Global trade has facilitated invasive species introductions, both intentional and accidental, with soil translocation emerging as a key vector. This study focuses on the potential spread of *Melanoplus differentialis (M. differentialis)*, an invasive North American grasshopper first detected in Ulsan, South Korea, in 2018. By 2020 it was designated an ecosystem-disturbing species, prompting habitat monitoring. In 2024, concerns arose that soil relocation during construction at a high-density outbreak site (Onsan Industrial Park) could inadvertently spread *M. differentialis* to the Seongam Municipal Landfill (Ulsan), where construction debris was moved. Surveys conducted at the landfill in May and September 2025 found no *M. differentialis*, only native grasshopper species. This absence may be due to egg masses being destroyed during construction or insufficient time for a population to establish after introduction. The findings underscore the importance of continued monitoring at translocation sites, as invasive grasshopper populations can proliferate rapidly even from low-level introductions. The results highlight the effectiveness of Early Detection and Rapid Response (EDRR) efforts in preventing the spread of *M. differentialis* beyond its initial habitat. Collaboration between the National Institute of Ecology, local government, and private sectors has successfully contained the species within its original site. This study underscores the need for vigilance and coordinated action in managing invasive species, especially those spread through human activities like soil and waste movement.

Keywords: Ecosystem-disturbing species, Invasive alien species, Management strategy, *Melanoplus differentialis*, Soil translocation

Introduction

The growth in logistics driven by international trade has increased opportunities for both intentional and unintentional introductions of alien species, and—along with rising trade volumes—the rate of first introductions, and thus the potential for subsequent biological invasions has not reached saturation but has continued to increase (Seebens *et al.*, 2021). Under the Convention on Biological Diversity (CBD) pathway classification adopted by Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Global Biodiversity Information Facility (GBIF), International Union for Conservation of Nature (IUCN), introduction pathways comprise six main categories. Within Transport–Contaminant, the

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transportation of habitat material subcategory explicitly covers the unintentional movement of organisms—including insects and molluscs—via the transfer of soil, mulch, leaf litter, and other habitat materials (Groom *et al.*, 2019; Harrower *et al.*, 2018; IPBES, 2023).

According to current study, the crown-Orthoptera emerged approximately 355 million years ago, and the crown-Caelifera diverged during the Carboniferous period around 320 million years ago (Song *et al.*, 2020). Most insects within Orthoptera oviposit in soil, and among them, only about 6% of species within the superfamily Acridoidea lay their eggs on or inside host plant tissues (Braker, 1990). Since soil temperature and moisture are key factors determining egg survival and development, acridids have evolved egg pods to support successful reproduction (Braker, 1990; Song *et al.*, 2015). The acridid egg pod is encased in a foam that buffers the eggs against excessive desiccation or flooding, and this adaptive foam has enabled successful hatching across a wide range of habitats—from humid wetlands to arid deserts with minimal soil moisture (Stauffer *et al.*, 2011). Due to these ecological characteristics, grasshoppers have been reported to invade new regions through the unintentional translocation of eggs during soil movement. *Stenocatantops splendens*, first recorded on Guam in 1984, was suggested to have been unintentionally introduced through the importation of ornamental potted plants (Schreiner, 1991). A direct case of introduction was also identified for *Schistocerca nitens (S. nitens)*, discovered in West Chop, Tisbury, Massachusetts, with its origin presumed to be a Monrovia nursery in Azusa, California (Pelikan, 2022). In addition, a mass introduction of *Melanoplus differentialis (M. differentialis)* was recorded on Martha's Vineyard, Massachusetts, in 2017, coinciding with the importation of nursery stock (Pelikan, 2022). Although the precise introduction pathway remains unclear, *S. nitens*—introduced to Hawaii as early as 1964—has been shown to negatively affect island vegetation. In South Korea, there is also a documented case of *Tettigonia jungi*, typically found in southern regions such as Jeju Island and Yeoseo Island, being observed in a *Miscanthus sinensis* habitat in Haneul Park, Sangam-dong, Mapo-gu, Seoul, a relatively recently developed urban park (Kim *et al.*, 2024a).

M. differentialis, native to North America, was first detected in South Korea on August 5, 2018, when an individual was found as a hitchhiker at Onsan Port. In 2020, a high-density population was confirmed within the Onsan National Industrial Complex, and as a result, the species was officially designated as an ecosystem-disturbing species under the Act on the Conservation and Use of Biological Diversity in December 2020 (Kang *et al.*, 2021; Kim *et al.*, 2024b). Since then, the National Institute of Ecology (NIE), in collaboration with the Ulsan Metropolitan Government and the Nakdong River Basin Environmental Office, has conducted habitat distribution monitoring of *M. differentialis* through the national ecosystem-disturbing species surveillance program. Based on the monitoring results, chemical control measures have been implemented at the identified sites (NIE, 2022; NIE, 2023; NIE, 2024). As a result, *M. differentialis* has not expanded beyond the original introduction site in the Onsan National Industrial Park, and its occupied habitat area has gradually decreased. However, the risk of artificial dispersal has emerged because soil and rock materials were relocated from the initial outbreak site, where the species had occurred at high densities, to nearby development areas.

In this study, we investigated soil translocation from these previously infested sites and conducted targeted surveys at the Ulsan Municipal Waste Incineration Facility Business Office, where the largest volume of soil had been relocated. Our results confirmed that *M. differentialis* has not yet established populations at the translocation site. This study highlights the importance of continuous surveillance to prevent further spread and provides critical baseline information for the management of invasive alien species in Korea.

Materials and Methods

Study site

We conducted our survey at the Seongam Municipal Solid Waste Landfill in Ulsan, where a debris flow was reported within the habitat of *M. differentialis*. The facility comprises a Closed Landfill, which operated from 1994 to 2012, and an Active Landfill, which has been in operation since 2012. The Closed Landfill covers a total area of 143,000 m^2, while the Active Landfill covers 2,615,000 m^2. The Active Landfill is subdivided into the Fly Ash Landfill and the Expansion Landfill (Phase I and Phase II). The Fly Ash Landfill has a total area of 14,400 m^2 with a total capacity of 135,000 m^3; the Expansion Landfill has a total area of 260,200 m^2 with a total capacity of 5,000,000 m^3. As of November 2023, 109,422 m^3 of capacity had been used in the Fly Ash Landfill and 1,323,253 m^3 in the Expansion Landfill (Fig. 1).

Sampling method

We surveyed the entire Seongam Municipal Solid Waste Landfill. In the Active Landfill, most areas were barren ground with no grassland; however, narrow grassland patches had developed along the edges, and these edge grasslands were included in the survey together with the continuous buffer grasslands along access roads. In the Closed Landfill, which has already undergone succession to a grassland ecosystem, we sampled along established trails; to account for potential additional spread, we also surveyed the Leachate Treatment Facility, Incineration

Facility, landscaped beds within parking areas, and unmanaged grasslands. Surveys were conducted on May 22, 2025, when nymphs were in the 1st-3rd instars, and on September 4, 2025, when adults were present. In May, we performed sweep-net sampling (10 sweeps every 50 m) and identified the captured grasshoppers. In September, we repeated the same sweep-net protocol and supplemented it with visual searches targeting fleeing adults (Fig. 2).

Fig. 1. Layout of Seongam Municipal Solid Waste Landfill. Closed Landfill operated from 1994 to 2012, and Active Landfill has been in operation since 2012. Active Landfill consists of Fly Ash Landfill and Expansion Landfill (Phase I and Phase II). Leachate Treatment Facility is located in the Southern area, along with Incineration Facility and Sewage Sludge Treatment Facility.

Result

Coordinated response

This result describes the process of identifying potential spread pathways and secondary habitats of *M. differentialis*, an ecosystem-disturbing species, in the course of ongoing distribution surveys and control efforts. Sites 1 and 2 in Fig. 3 are located near the Dalpo Pier area of the Port of Onsan and had remained undeveloped, open spaces owned by LS MnM Co., Ltd. and Hankuk Paper Co., Ltd., respectively. Site 1, in particular, was one of the key locations where *M. differentialis* had been observed at high density across a wide grassland area and served as critical evidence leading to its designation as an ecosystem-disturbing species in 2020.

However, during a full-scale survey of *M. differentialis* conducted in May 2024 across the Onsan National Industrial Park, it was confirmed that construction had begun at Site 1, with excavation underway using heavy equipment. In a follow-up adult survey conducted in August 2024, it was further observed that Site 2 had also begun development, including active digging operations.

These developments were reported to Ulsan Metropolitan City and the Nakdong River Basin Environmental Of-

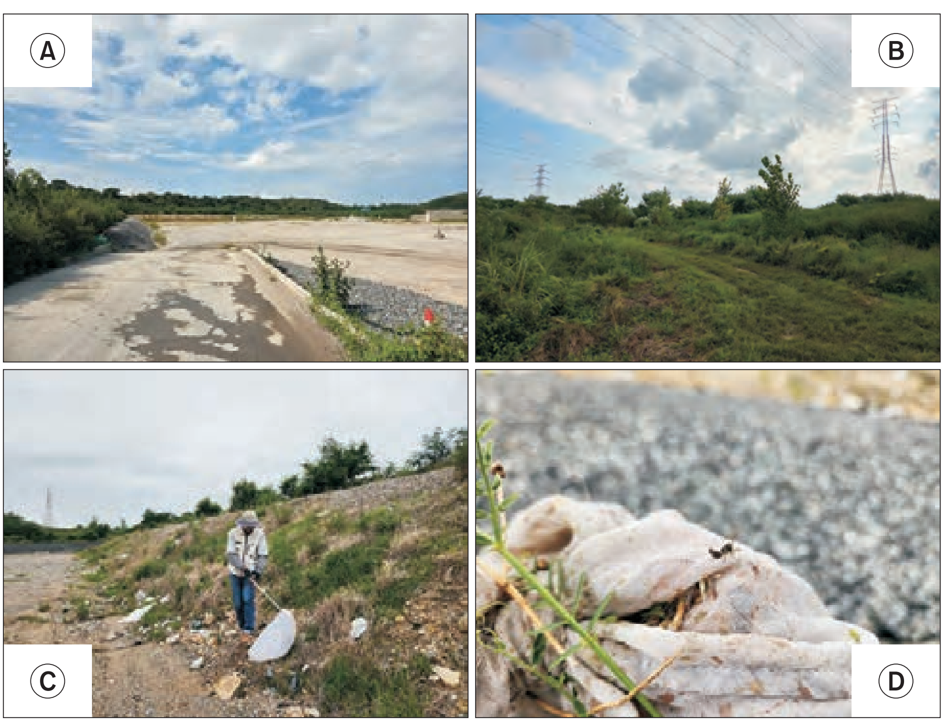

Fig. 2. Field views and sampling at the Seongam Municipal Solid Waste Landfill. (A) Overview of the Active Landfill; (B) overview of the Closed Landfill; (C) sweep-net sampling in edge grassland within the Active Landfill, where partial succession is evident; and (D) grasshopper captured by sweeping (nymph of *Shirakiacris shirakii*, May).

Fig. 3. Coordinated detection and verification process of debris transport within the *M. differentialis* habitat, with Site locations in the Onsan National Industrial Complex. The left panel illustrates the sequential response process—from expert risk recognition to government engagement and investigation initiation—for identifying potential secondary habitats based on predicted spread. The right panel shows the map of confirmed *M. differentialis* occurrences (as of August 2023) and the locations of ① and ② debris relocation sites, as well as ③ the site of interagency collaboration. NIE, National Institute of Ecology; MSW, Municipal Solid Waste Landfill; *M. differentialis, Melanoplus differentialis.*

fice. The research team emphasized to city officials that such soil displacement could facilitate the spread of *M. differentialis*, and urged that the movement of soil and debris be traced. In response, Ulsan Metropolitan City provided detailed information on soil relocation on September 4, 2024. According to the data, construction at Site 1 was scheduled from November 2023 to November 2024, and the soil was being transported to the Seongam Municipal Solid Waste Landfill (Fig. 3).

Following this report, the NIE informed Ulsan Metropolitan City of its plan to begin monitoring the Seongam Municipal Solid Waste Landfill starting in 2025. Subsequently, Ulsan Metropolitan City reported back that a specimen suspected to be *M. differentialis* had been captured during their own preliminary investigation at the landfill site.

Grasshopper survey

On May 22 and September 4, 2025, the Seongam Municipal Solid Waste Landfill was surveyed during both the nymphal (instars 1-3) and adult stages of *M. differentialis*. Priority was given to the Active Landfill area, as it was presumed to have received translocated debris from the high-density habitat of *M. differentialis*. However, the area consisted largely of barren ground with no grassland, prompting the inclusion of surrounding unmanaged grass patches and roadside plant beds in the survey. The Closed Landfill, having undergone significant ecological succession into grassland, was considered more suitable for grasshopper habitation and was therefore investigated in full. Additionally, the Incineration Facility and adjacent parking lot at the entrance of the landfill were also surveyed.

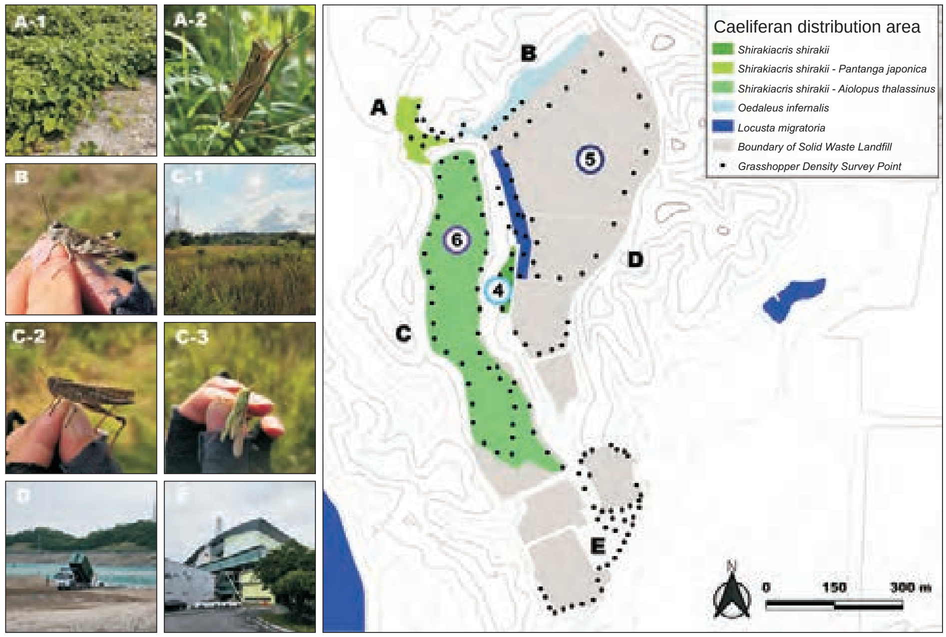

Fig. 4. Survey results of grasshoppers at the Seongam Municipal Solid Waste Landfill. The locations corresponding to ④, ⑤, and ⑥ in Fig. 3 are indicated. Although points ⑤ and ⑥ were surveyed across the entire landfill area, they are labeled under "Active Landfill" and "Closed Landfill" for convenience. Surveys were conducted at each designated Grasshopper Density Survey Point. According to the survey legend, the following species were identified: *Sphingonotus shirakii*, *Pantanga japonica*, *Aiolopus thalassinus*, *Oedaleus infernalis*, and *Locusta migratoria*. Site overviews and photographs of the observed grasshopper species are provided on the left side of the map. (A) *Shirakiacris shirakii - Pantanga japonica*, (B) *Oedaleus infernalis*, (C) *Shirakiacris shirakii - Aiolopus thalassinus*, (D) Active Landfill Area, and (E) Incineration Facility Area.

No individuals of *M. differentialis*, an ecosystem-disturbing species, were detected during either survey. Site A, located at the interface between the landfill and adjacent forested area, was dominated by *Pueraria montana*, and yielded observations of *Shirakiacris shirakii (S. shirakii)* and some individuals of *Pantanga japonica*. Site B, situated along the peripheral edge of the Active Landfill, was a highly disturbed area dominated by Conyza canadensis, where *Oedaleus infernalis* was the most frequently observed species. Throughout the landfill, *S. shirakii* was commonly present; notably, *Locusta migratoria* was found in plant beds adjacent to the Active Landfill. The Closed Landfill, having progressed further in grassland succession, supported a wider range of species including *Aiolopus thalassinus* and multiple members of the subfamily Conocephalinae, such as *Conocephalus exemptus*. No Orthopteran species were observed within the Incineration Facility (Fig. 4).

Discussion

Absence & management

The survey of the Seongam Municipal Solid Waste Landfill revealed no presence of *M. differentialis*. Despite the Active Landfill being the most likely site for the introduction of *M. differentialis*, no grasshopper species were found in this area, and only native grasshopper species were observed in the surrounding areas, including the Active Landfill perimeter and the Closed Landfill. Based on these findings, three possible reasons for the absence of *M. differentialis* in the relocated soil were inferred:

1. Egg pods may have been destroyed by mechanical pressure during excavation and compaction, or buried at depths too great for successful hatching.
2. The initial stage of introduction involved a very low population density, or the introduction went unnoticed during the process.
3. Due to the proper handling of the imported waste, it was unlikely that the landfill received *M. differentialis* compared to other cases, such as those involving fruit trees or horticultural plants.

Given that females of *M. differentialis* typically oviposit egg pods at a depth of approximately 5 cm below the soil surface (Kim *et al.*, 2024a), the first hypothesis may have contributed to egg mortality to some extent. However, because soil from the entire LS MnM Co., Ltd. site was transported to the Seongam Municipal Solid Waste Landfill, it is reasonable to assume that all egg pods laid within this area were secondarily relocated in a scattered manner. Moreover, numerous other cases of introduction associated with soil translocation have been reported, suggesting that the first hypothesis is unlikely to represent the primary explanation for the absence of *M. differentialis* at the landfill. This conclusion is based on numerous documented cases of unintentional invasions via soil movement (Kim *et al.*, 2024a; Pelikan, 2022; Schreiner, 1991).The second hypothesis suggests that the first debris relocation occurred in November 2023, and while the process continues, the population density was too low to detect at this time. In fact, *M. differentialis* hatches in April and the adults are present from June to November in Korea (Kim *et al.*, 2024b; NIE, 2022; NIE, 2023; NIE, 2024). Thus, the debris moved during construction in November 2023 likely contained egg masses in a dormant state, and it is assumed that they hatched in 2024. By the time of the surveys in May and September 2025, the second generation would likely have emerged, but there was insufficient time for the population density to increase. However, previous monitoring of ecosystem-disturbing species has shown that *M. differentialis* populations can rapidly increase in the following year, even in locations where only a few individuals were found the previous year, making this hypothesis uncertain.

The third hypothesis suggests that the imported waste was appropriately processed, making it difficult for *M. differentialis* to enter the landfill. The waste management process at the Seongam Municipal Solid Waste Landfill consists of several stages: 1) collection and transportation via waste collection vehicles, 2) weighing of waste through weight registration, 3) inspection for illegal waste, 4) unloading and monitoring for illegal waste, 5) compaction using bulldozers and heavy machinery, 6) daily pest control, and 7) covering with high-quality soil. During the September survey, both the unloading process and pesticide spraying by a pest control vehicle were observed. The compaction process likely destroyed the egg masses of the initially introduced grasshoppers, and any surviving grasshoppers were likely eliminated during the daily pest control measures. Therefore, the second and third hypotheses are considered more plausible. However, since soil relocation from the high-density *M. differentialis* habitat continues at the landfill, it is essential to continue monitoring for the presence of *M. differentialis* during future surveys. Additionally, based on another case of grasshopper movement observed at Haneul Park (*Tettigonia jungi*; Kim *et al.*, 2024a), regular pest control measures should also be considered for projects like street tree planting or large-scale park developments, where soil movement and waste management processes similar to those at the landfill may occur.

Importance of collaboration

To minimize the ecological and economic impacts of invasive alien species, the EDRR strategy is considered essential (Simberloff *et al.*, 2013). Since the initial detection of *M. differentialis* near the Onsan National Industrial Park in Ulsan in 2020, containment and eradication efforts have been implemented through close collaboration among NIE, Ulsan Metropolitan City, and private-sector companies operating within the industrial complex.

The NIE conducted intensive field surveys to delineate the distribution range of *M. differentialis* and assessed population densities to establish priority areas for control. Based on these findings, Ulsan Metropolitan City developed a rapid response strategy, designated control zones, secured municipal funding, and coordinated annual control efforts in cooperation with resident private companies.

As a result, the areal extent of *M. differentialis* occurrence has shown a consistent decline, with seasonal distribution areas decreasing from 81 ha in 2021 to 29 ha in 2022, 13 ha in 2023, and 4 ha in 2024 (NIE, 2024). Furthermore, such outcomes were made possible through the sustained collaborative framework between expert groups and government authorities. This cooperation enabled timely tracking of potential spread resulting from intentional or unintentional soil relocation caused by construction within high-density habitats, as demonstrated in this study. It also facilitated immediate responses to other potential scenarios—such as the inadvertent dispersal of alien species via waste collection activities within invaded habitats.

This outcome exemplifies a successful case of early-stage invasive species containment through coordinated action among governmental agencies, research institutions, and private-sector stakeholders (Bauer *et al.*, 2015; Marchioro & Faccoli, 2021), and serves as a model for effective implementation of the EDRR framework.

Author Contributions

Conceptualization: JS, JA. Formal analysis: JS. Funding acquisition: JA. Investigation: JS, JA. Methodology: JS. Supervision: JA. Visualization: JS. Writing – original draft: JS. Writing – review & editing: JS.

Conflict of Interest

The authors declare that they have no competing interests.

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Comparative Analysis of Fallen Rice Counts in Straw-Retained and Non-Retained Fields under Payments for Ecosystem Services Schemes: A Case Study of Gunsan, Korea

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ABSTRACT

This study evaluated the effects of the rice straw retention project, implemented in Napo-myeon, Gunsan-si, under the payments for ecosystem services (PES) schemes, on providing food for wintering waterfowl. The amount of fallen rice was measured at four sites in both PES and non-PES fields. In all comparison pairs, the count of fallen rice grains in the PES fields was 3-11 times higher than in the non-PES fields ($P<0.05$). The effect size (r) ranged from 0.386 to 0.790, demonstrating substantial significance. This trend is consistent with similar studies conducted overseas. Therefore, the PES project appears to be achieving its intended goals, and these findings provide a foundation for the scientific evaluation of domestic PES policies.

Keywords: Geumgang (river) estuary, Rice straw retention, Supporting services, Waterfowl, Wintering birds

Introduction

Agricultural landscapes are not merely spaces for food production; they are vital foundations that provide diverse ecosystem services to human society. Rice-growing regions, in particular, not only provide food for humans but also offer winter food sources for birds through waste rice and rice straw after harvest (Lancaster & Askren, 2023). In paddy ecosystems, waterfowl and rice harvest residues (spilled rice, rice straw) are closely interconnected. Fallen rice left after harvesting serves as a critical food resource for key bird species like the Bean Goose (Anser fabalis) (Greer *et al*., 2009).

The Geumgang (River) estuary is a key site within the East Asian-Australasian Flyway (EAAF) Partnership, serving as a wintering or stopover site for hundreds of thousands of waterfowl annually. Overseas studies indicate that conservation methods such as leaving rice straw intact enhance rice residue preservation and increase waterfowl access to food (Bird *et al*., 2000; Kross, 2006). Waterfowl foraging activities also accelerate rice straw decomposition, contributing to improved soil health. As a certain level of waterfowl density is recognized as important for habitat maintenance (Havens *et al*., 2009; Miller *et al*., 2010), maintaining and managing food resources in agricultural lands is vital for migratory bird conservation, and the interaction between rice paddies and waterfowl can serve as an effective management strategy.

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Payments for ecosystem services as a policy tool

Payments for ecosystem services (PES) are presented as a policy tool for linking agriculture and biodiversity conservation. PES is defined as "a system whereby at least one buyer voluntarily and conditionally compensates at least one provider for land use that delivers clearly defined environmental services" (Wunder, 2005). Such a system can institutionally realize mutual benefits between production and conservation by providing farmers with economic incentives for ecosystem conservation (Bird *et al*., 2000).

As an internationally recognized policy tool, PES programs are evaluated based on key elements such as cost-effectiveness, goal-oriented design, stakeholder participation, and systematic monitoring and performance. PES implemented in various countries reflects local characteristics through strategies like differential payments and opportunity cost reflection. However, the lack of transparency in fund management and scientific performance monitoring is noted as a limitation in implementation (Pham *et al*., 2015; Yost *et al*., 2020). In Korea, indicator-based evaluation systems and cost-effectiveness-based compensation are being proposed for the forestry and agriculture sectors (Ahn, 2013; Jung & Park, 2022).

Current status and research gap

PES-based rice straw retention projects are being implemented in several migratory bird arrival areas in Korea. Leaving rice straw in paddy fields enhances the preservation of fallen rice and contributes to the supply of winter forage resources (Yoo *et al*., 2008). However, quantitative research on how this management practice affects the conservation of waterfowl populations remains insufficient. The specific effects of rice straw retention on fallen rice conservation and forage resource maintenance have not been clearly verified.

For the conservation of wintering birds and waterfowl, securing food sources and maintaining habitat functionality are essential (Yoo *et al*., 2008). Domestic studies demonstrate that preserving winter rice straw and fallen rice is linked to maintaining overwintering bird populations and that forming spatial networks of core habitats and migration corridors is important (Shim *et al*., 2024). Research is underway to quantify habitat value through Ecosystem Service Indicators and avian community analysis (Choi *et al*., 2024).

Study objectives

There is an ecological link between rice residue conservation and bird food sources. However, quantitative evaluations of how rice straw retention projects affect waterfowl food provision remain limited. This study investigates the amount of fallen rice retained at a rice straw retention project site in Napo-myeon, Gunsan City, near the Geumgang (River) estuary, and analyzes the impact on maintaining food resources for waterfowl during winter. This study represents an empirical evaluation of domestic PES effectiveness and will provide foundational data for establishing future policies linking agricultural management and migratory bird conservation.

Materials and Methods

Study site

The study targeted cultivated paddy fields in Napo-myeon, Gunsan-si, Jeollabuk-do, which had undergone land consolidation (Fig. 1). The study site, a migratory bird arrival area, is located along the Geumgang (River). It is the area where the rice straw retention project, aimed at providing food for wintering birds, was implemented. This project covered the area from the northern bank of the Geumgang (River) to the southern boundary of Local Road 706. In 2024, the survey year, the contracted area for rice straw retention in the target region was 1,813,536 square meters. The total cultivated rice paddy area in the target region was 3,525,042 square meters, with the rice

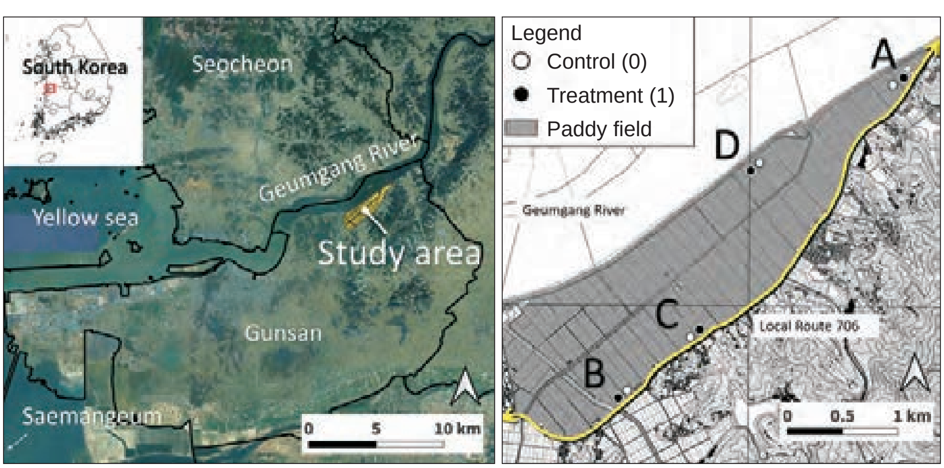

Fig. 1. Location of study sites. Each of the four sites comprised one control (0) and one treatment (1) plot, labeled A, B, C, and D.

straw retention area accounting for 51.5% of the total paddy area.

Survey and analysis methods

The study sites comprised a total of 4 locations and 8 plots. Each set consisted of one plot of rice paddy with straw retention and one adjacent non-retention plot, allowing for comparative analysis of fallen rice counts between the two types of paddies. To minimize the impact of fallen rice loss due to waterfowl foraging activity, sites were selected in areas close to residential areas and roads where human disturbance was expected to reduce bird activity. In such locations, two adjacent plots (one project and one non-project) separated by a farm road were chosen. The survey randomly selected 20 quadrats measuring 20×20 cm per field, totaling 160 quadrats, to determine the number of fallen rice grains. Field surveys were conducted over two days, December 17-18, 2024. Survey results were analyzed for group differences across four pairs (A0 vs. A1, B0 vs. B1, C0 vs. C1, D0 vs. D1), naming the four points A through D, project plots as 1, and non-project plots as 0.

Statistical analysis involved assessing normality of the fallen rice data for each group using the Shapiro-Wilk test (Shapiro & Wilk, 1965). Since the analysis confirmed non-normal distribution in all groups ($P<0.05$), the Mann-Whitney U test was used to analyze differences between groups (Mann & Whitney, 1947). When significant differences between groups were identified, the effect size (r) was additionally calculated to quantify the practical significance of the difference. The calculated effect size was interpreted according to Cohen's (1992) criteria: approximately 0.1 indicates a small effect, ~0.3 a medium effect, and ~0.5 a large effect.

Results

Descriptive statistics

The descriptive statistics for the number of fallen rice grains surveyed in the target area paddies are shown in Table 1. The analysis revealed that paddies under the rice straw retention project (1) generally showed a higher number of fallen rice grains compared to non-project paddies (0). At all sampling points (A, B, C, D), the median for the project field was significantly higher than the median for the non-project field. Notably, at point D, the median for the non-project field (0) was very low at 1.0, while the project field (1) showed a median of 11.5, demonstrating the substantial impact of rice straw retention. Overall, the data distribution showed the mean higher than the median, indicating a tendency for fallen rice to concentrate in specific quadrats. Notably, D1 exhibited high variability, encompassing a wide range (2-201) and including extreme outliers (144, 201). The boxplot (Fig. 2) visually presents a distinct difference in fallen rice distribution between project and non-project fields.

Intergroup difference analysis

The difference in fallen rice counts between rice fields with straw retention (1) and adjacent non-project fields (0) was analyzed using the Mann-Whitney U test (Table 2). The analysis revealed that in all four pairs, the fallen rice count in the rice straw retention project field (1) was statistically significantly higher ($P<0.05$) than in the non-project field (0). Furthermore, the calculated effect size (r) showed a 'Large Effect' (close to or exceeding 0.5) in the pairs A0 vs. A1 (0.467), C0 vs. C1 (0.542), and D0 vs. D1 (0.790). The B0 vs. B1 (0.386) pair also exceeded 0.3, showing a 'Medium to Large Effect.' This quantitatively demonstrates that the effect of rice straw retention on fallen rice preservation is substantial. The highest effect size was observed at site D (r=0.790), indicating that the

Table 1. Descriptive statistics of fallen rice counts per quadrat at study sites (n=20)

Site	Group	Mean	Median	SD	Min	Max
A	0	7.10	6.5	6.09	0	20
	1	29.60	24.5	28.15	0	116
B	0	10.60	2.5	15.00	0	43
	1	21.65	12.0	20.70	1	64
C	0	6.35	5.5	5.63	0	22
	1	18.30	16.5	13.21	3	59
D	0	1.40	1.0	1.60	0	22
	1	31.45	11.5	51.85	2	201

Group 1 (treatment plot) refers to the paddy field where rice straw was retained after harvest, whereas Group 0 (control plot) refers to the field where it was not.
SD, standard deviation.

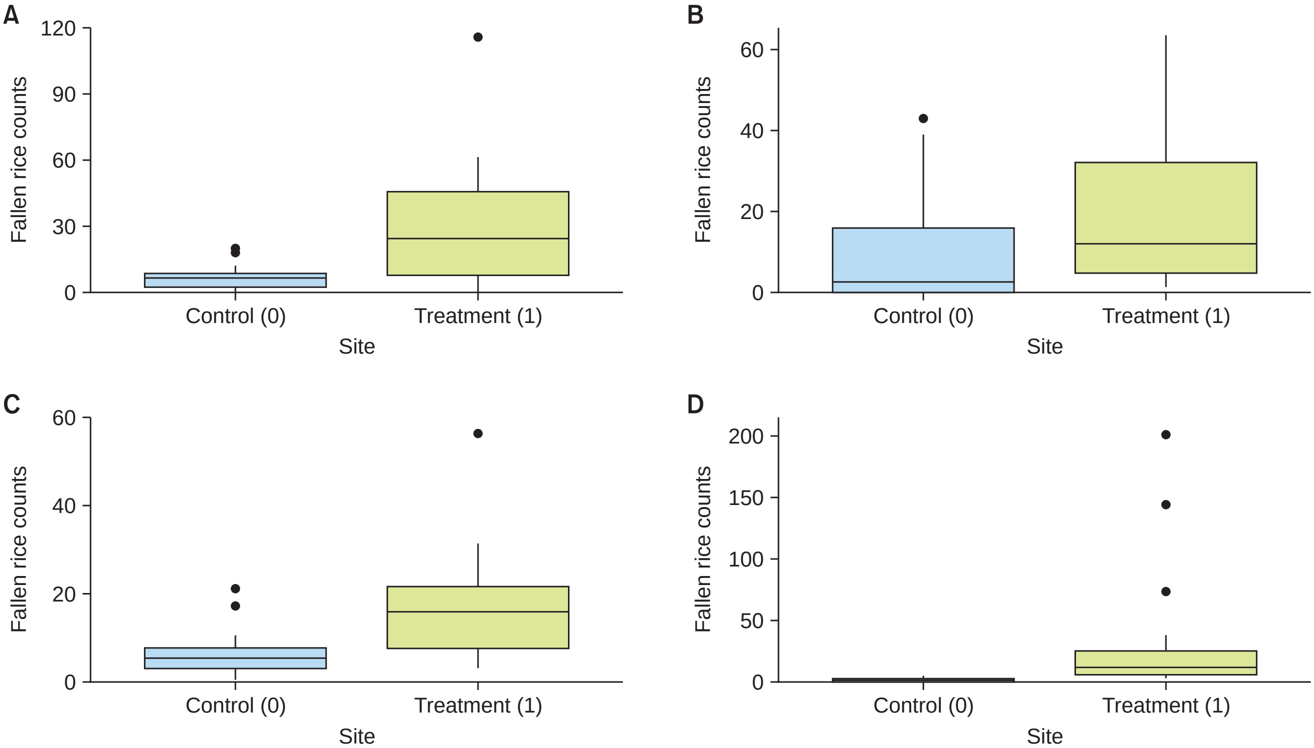

Fig. 2. Boxplot comparison of fallen rice counts by site (A-D) and pair. (A), (B), (C), and (D) refer to Fig. 1.

Table 2. Mann-Whitney U test comparison of fallen rice counts by four paired sites

Comparison pair	W value	*P*-value (two-tailed)	Median 1 (treatment plot)	Median 0 (control plot)	Effect size (r)
A0 vs. A1	90.5	0.003138	24.5	6.5	0.467
B0 vs. B1	109.5	0.014600	12.0	2.5	0.386
C0 vs. C1	73.0	0.000607	16.5	5.5	0.542
D0 vs. D1	16.5	5.865×10^{-7}	11.5	1.0	0.790

Based on Cohen (1992), effect size (r) values of approximately 0.1, 0.3, and 0.5 indicate small, medium, and large effects, respectively.

effect of preserving fallen rice in the project field (D1) is very large compared to the extremely low number observed in the non-project field (D0).

Discussion

The results of this study empirically demonstrate that the rice straw retention project implemented in the Geumgang (River) estuary region has a highly significant effect on providing a food source for waterfowl. Not only did the project fields show a significantly higher number of fallen rice grains compared to non-project fields in all comparison pairs, but the magnitude of this difference (effect size r=0.467-0.790) was also statistically significant. Based on the median values, the difference in fallen rice counts between project and non-project fields ranged from a minimum of 3 times (Site C) to a maximum of 11 times (Site D). This result aligns with prior studies in California and Arkansas, USA. Bird *et al*. (2000) and Havens *et al*. (2009) also reported that post-harvest field management practices caused over threefold differences in waterfowl food source availability. Notably, the largest effect size (r=0.790) was observed in the comparison with non-project paddies (D0), where rice straw residues were nearly absent. This suggests that without rice straw retention, fallen rice either exists below levels accessible to wintering birds or is rapidly depleted.

The ecological significance of these findings lies in demonstrating that agricultural activities themselves can generate ecosystem services for wintering bird conservation. The foraging activities of waterfowl create 'mutual benefits' that positively impact not only the utilization of fallen rice but also agricultural productivity (Bird *et al*., 2000). During the feeding activities of waterfowl in paddy fields, rice straw residues are physically shredded and come into contact with the soil, accelerating the decomposition rate of the straw. This reduces the cost and labor required for farmers to manage rice straw during the next year's tillage, making rice straw retention a sustainable management practice that simultaneously achieves biodiversity conservation goals and benefits farmers. This mutually beneficial structure is also significant in the Geumgang (River) estuary, as it serves as a key stopover site along the EAAF (Greer *et al*., 2009).

This study represents a rare instance of quantitatively and empirically evaluating the effectiveness of domestic PES schemes. As noted in previous studies, the success of PES programs hinges on systematic monitoring and scientific performance evaluation (Engel *et al*., 2008; Yost *et al*., 2020). The empirical results of this study hold the following policy implications. First, it numerically demonstrates that the Napo-myeon rice straw retention project is effectively achieving its goal of providing a wintering bird food source. Second, the quantitative benchmarks established in this study can be utilized for future cost-effectiveness evaluations of PES projects. This will aid in selecting optimal participating regions and determining compensation levels within limited budget constraints (Jung & Park, 2022). Third, the quadrat survey and random sampling method employed in this study present a repeatable and comparable monitoring methodology. This can serve as a practical solution to the challenge of "the absence of a scientific performance monitoring system."

This study has the following limitations. First, the data used for analysis were obtained from short-term field surveys and do not reflect changes in fallen rice quantities throughout the entire period of wintering bird arrival. Additionally, environmental variables such as distance to water sources, human disturbance, and agricultural management history were not fully controlled in the site selection process, which could influence the availability of fallen rice.

Therefore, it is necessary to quantitatively measure the residual amount and depletion rate of fallen rice through periodic surveys (at least once per month) and to understand the foraging pattern during the wintering period. Furthermore, the study focused on evaluating fallen rice without directly examining its correlation with biological indicators such as the arrival timing and population size of actual waterfowl populations. Consequently, follow-up research should track waterfowl populations across the entire wintering season to establish quantitative relationships between the rice straw retention program, annual variations in food availability, waterfowl population dynamics, and the relationship between foraging sites and resting habitats.

In conclusion, verifying the institutional effectiveness of domestic PES policies during their initial growth phase is crucial for enhancing policy credibility and scalability. The quantitative empirical results of this study are expected to strengthen the basis for decision-making by policy makers and provide the scientific foundation for domestic PES projects to the academic community. If a broad-scale, long-term monitoring and evaluation system is established in the future, the rice straw retention project under the PES schemes will become a sustainable development model for wintering bird conservation and rural ecosystem management in Korea.

Author Contributions

Conceptualization: TC. Data curation: HM, BK, TL, TC, PJ. Formal analysis: TC, PJ. Funding acquisition: TC. Investigation: HM, BK, TL, TC, PJ. Writing – review & editing: TC, PJ.

Conflict of Interest

The authors declare that they have no competing interests.

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Comparative Analysis of Avian Assemblages between an Urban Ecological Restoration Site and an Adjacent Forest: The Case of Mt. Sorasan Restoration Site, Iksan, Korea

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ABSTRACT

Although urban ecological restoration projects are actively implemented in response to urbanization, research evaluating their ecological effects in relation to adjacent natural ecosystems remains limited. This study assessed the ecological impacts of an urban restoration project by comparing wild bird assemblage structures between the Mt. Sorasan Nature Garden (Jayeon-madang) project, an urban ecological restoration site in Iksan, South Korea, and its adjacent existing forest. The restoration site, in its early post-construction phase, had approximately 45% of its area planted with woody species, including pines. Wild bird surveys were conducted in both habitats over one year (May 2017-April 2018), followed by statistical analysis. Results showed significant differences in bird assemblage structure between the sites (permutational multivariate analysis of variance, $P<0.001$). The adjacent forest, supported by a stable, long-established woodland, exhibited higher species diversity (H'=3.07) and was characterized by foliage gleaners (e.g., Paridae) and bark/trunk foragers (e.g., Picidae). In contrast, the restoration site, with small trees and insufficient cover due to its recent establishment, had lower species diversity (H'=2.38) and limited influx of forest-dwelling birds. However, its open grasslands and wetlands provided feeding and resting habitats for aquatic and ground-foraging birds. In conclusion, although the early-stage restoration site remains functionally limited as a forest, it complements the adjacent forest by creating heterogeneous habitats, thereby enhancing overall urban avian diversity. This study highlights the need for future restoration efforts to extend beyond simple tree planting and incorporate long-term habitat management that accounts for vegetation succession processes.

Keywords: Foraging guilds, Indicator species, Multivariate analysis, Restoration effectiveness

Introduction

The rapid global expansion of urban areas accelerates habitat loss and fragmentation, leading to the isolation of habitats within cities and a reduction in biodiversity (Hagen *et al.*, 2017). Many studies have predicted a significant future loss of biodiversity if this urban expansion continues (Newbold *et al.*, 2015; Simkin *et al.*, 2022). In response to this problem, the necessity of ecological

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restoration projects to restore degraded natural environments and recover ecological functions within cities has been internationally emphasized. The United Nations (UN) declared 2021-2030 as the UN Decade on Ecosystem Restoration, and both the Kunming-Montreal Global Biodiversity Framework (Convention on Biological Diversity, 2022) and the European Union (EU) Biodiversity Strategy for 2030 (European Commission, 2021) established ecological restoration as a key objective. In South Korea, many urban ecological restoration projects have been promoted, and institutional implementation of natural environment restoration projects was strengthened with the revision of the Natural Environment Conservation Act in 2021.

However, evaluations of the ecological effects of these restoration projects remain insufficient (Ji *et al*., 2024; Lee, 2023). In Korea, the Nature Garden (Jayeon-madang) ecological restoration project, promoted since 2012 as an ecological restoration initiative, has resulted in the completion of a total of 18 sites completed as of 2019 (Architecture and Urban Research Institute, 2019). However, research concerning the effectiveness of such restoration efforts is still lacking. Only a few studies have been reported to date, such as the heat reduction effect of urban ecological restoration sites (Choi *et al*., 2017), the origin of planted species (Lee *et al*., 2020), and comparison of wild bird assemblages before and after restoration (Kim *et al*., 2020).

Against this backdrop, this study surveyed wild bird assemblages to evaluate the restoration effects of an urban ecological restoration project. Wild birds serve as indicator species for measuring ecosystem health due to their high mobility and sensitivity to environmental changes (Gregory & van Strien, 2010). Habitat isolation and degradation caused by urbanization directly impact the movement routes, breeding, and foraging success of wild birds, resulting in a reduction in the abundance of specific species and the proliferation of a few species highly adapted to urban environments (Bellocq *et al*., 2017; McKinney, 2006; Valente-Neto *et al*., 2021). Prior research has focused on identifying factors influencing bird species composition, occurrence patterns, habitat structure, impervious surface cover, and landscape heterogeneity due to urbanization (Souza *et al*., 2019). These wild bird assemblage metrics are effective indicators for assessing the ecological quality and functionality of restored habitats.

Therefore, this study comparatively analyzed the wild bird assemblage structure between an artificially created urban ecological restoration site and its adjacent, existing natural forest ecosystem. The study site, Mt. Sorasan Nature Garden was established in 2015. This study aimed to identify the habitat functions and limitations of the restoration area linked to the adjacent pine forest for wild birds through surveys and analyses conducted during the initial restoration period (2017-2018). Furthermore, it sought to establish baseline data for long-term monitoring and provide scientific evidence for the improvement of ecological restoration projects.

Materials and Methods

Overview of the study sites

The study was conducted targeting the Mt. Sorasan Nature Garden, an urban ecological restoration site located in Iksan, Jeonbuk Special Self-Governing Province, and its adjacent forest (Fig. 1). The total survey area covered approximately 8 ha, comprising the restoration site (39,757 m^2) and the adjacent forest (40,815 m^2), which were nearly similar in size. The restoration site was previously an area of farmland, buildings, and reed wetlands. Following the restoration project, completed in December 2015, the site was configured as a mixed habitat including pine-dominant woody planting (44.8%) linked to the adjacent forest, grassland (20.1%), and wetland (24.9%). The main planted woody species included *Pinus densiflora* (24.2%), *Chionanthus retusus* (6.6%), *Celtis sinensis* (6.1%), and *Sorbus alnifolia* (2.6%), all of which supply preferred food sources for wild birds. At the time of the survey in 2017, the short period since restoration resulted in minimal tree growth and vegetation that exhibited a

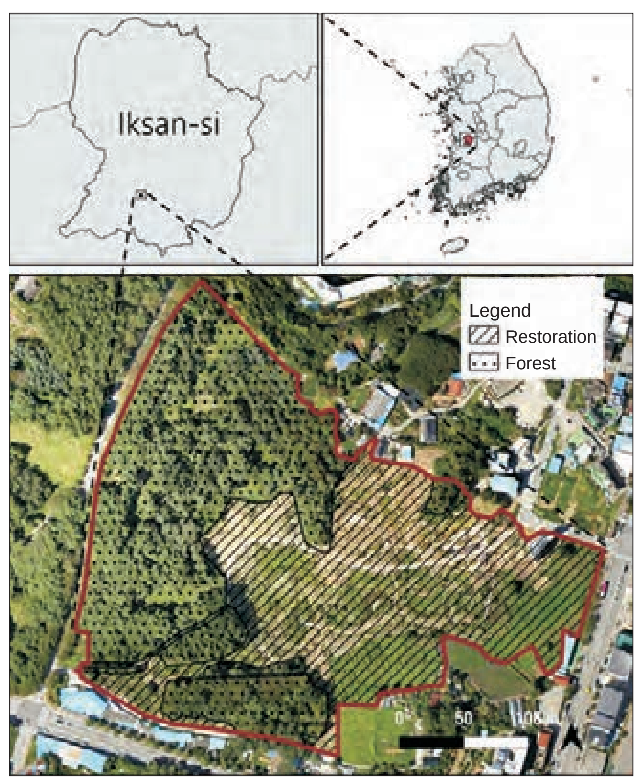

Fig. 1. Location of study site.

single-layered structure with sparse shrub layer planting. In contrast, the adjacent forest was a multi-layered woodland that distinctly contrasted with the restoration site. It was dominated by mature woody vegetation, accounting for approximately 90% of the area, primarily featuring *Pinus densiflora* (47.5%), *Robinia pseudoacacia* (11.8%), *Prunus* spp. (9.4%), and *Quercus acutissima* (7.9%), and possessed high vegetation volume across vegetation layers (Choi *et al*., 2019) (Table 1; Fig. 2).

Wild bird survey methods

The survey period was one year, from May 2017 to April 2018, with one day of surveying conducted monthly, totaling 11 surveys. The line-transect method was used, following a predetermined route after sunrise on clear days, and observed species were identified by sight with binoculars and by calls. The survey intensity was controlled by investigating the restoration site (4 ha) and the adjacent forest (4 ha), which are nearly similar in size, for the same amount of time (30 minutes each). The species name and abundance of all wild birds encountered during the survey were recorded, and species classification followed the National Species List of Korea (National Institute of Biological Resources, 2024).

Analysis methods

To compare the bird assemblage characteristics between the two habitats, the total species richness and total abundance for the overall period and by season were calculated. The Shannon–Weaver species diversity index (H') was calculated to assess the diversity of each habitat. Furthermore, foraging guilds were analyzed to understand the influence of habitat structure on bird occurrence. Foraging guilds were categorized based on the primary foraging space and behavior: aquatic forager (AF), aerial insectivore (AI), bark/trunk forager (BF), foliage gleaner

Table 1. Area and ratio by actual vegetation type

	Type	Area (m^2)	Ratio (%)
Forest	F1. *Pinus densiflora*	19,241	47.5
	F2. *Robinia pseudoacacia*	4,797	11.8
	F3. *Prunus yedoensis*	3,809	9.4
	F4. *Quercus acutissima*	3,209	7.9
	F5. *Pinus rigida*	2,300	5.7
	F6. *Castanea crenata*	2,295	5.7
	F7. *Populus tomentiglandulosa-Castanea crenata*	482	1.2
	F8. Bamboo	590	1.5
	F9. Cemetery	3,846	8.7
	F10. Field	246	0.6
	Subtotal	40,815	100.0
Restoration	R1. *Pinus densiflora*	9,624	24.2
	R2. *Chionanthus retusus*	2,625	6.6
	R3. *Sorbus alnifolia*	1,026	2.6
	R4. *Celtis sinensis*	2,407	6.1
	R5. *Salix koreensis*	1,158	2.9
	R6. *Prunus yedoensis*	862	2.2
	R7. *Diospyros kaki*	104	0.3
	R8. Tall grass area	2,247	5.6
	R9. Lawn	1,546	3.9
	R10. Other grassland	4,179	10.5
	R11. *Phragmites australis*	6,349	16.0
	R12. *Typha orientalis-Zizania latifolia*	3,399	8.6
	R13. Water surface	155	0.4
	R14. Facilities	4,076	10.3
	Subtotal	39,757	100.0

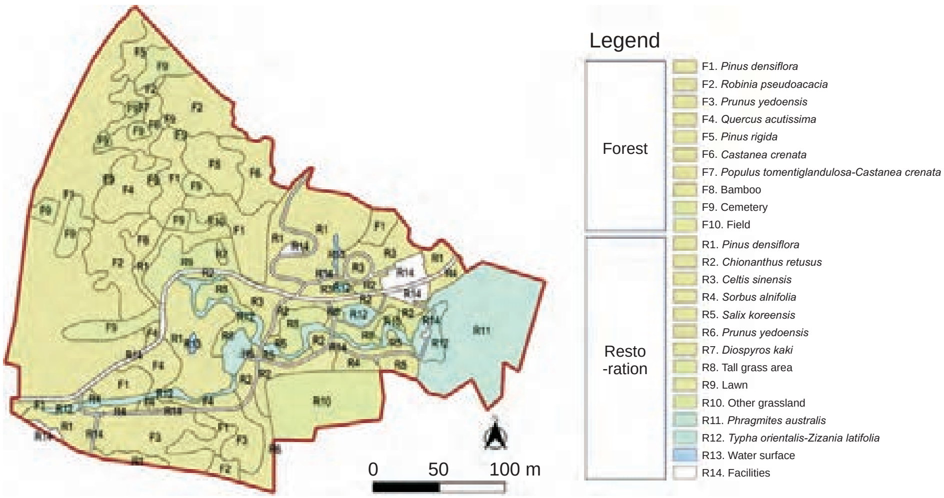

Fig. 2. Status map of actual vegetation type.

Table 2. Maximum species richness and abundance of avian assemblages in restoration and forest

	Restoration					Forest				
	Spring	Summer	Autumn	Winter	Total	Spring	Summer	Autumn	Winter	Total
Richness	14	13	12	16	28	20	19	17	19	30
Abundance	82	101	71	82	179	84	91	83	109	156
Species diversity (H')	1.99	1.59	1.72	1.95	2.38	2.68	2.51	2.52	2.67	3.07

(FG), ground forager (GF), and omnivore/generalist (OG).

Multivariate statistical analysis was performed to quantitatively verify the differences in wild bird assemblage structure between the two habitats. Permutational multivariate analysis of variance (PERMANOVA), a nonparametric multivariate analysis of variance, was applied to test for statistically significant differences in the bird assemblage structure between the restoration site and the forest. This method is suitable for ecological data that does not satisfy the assumption of normality and is a robust method for testing differences between groups based on distance metrics. Non-metric Multidimensional Scaling (NMDS) was used to visually complement the PERMANOVA results and represent the degree of similarity between assemblages in a two-dimensional space. Finally, similarity percentages (SIMPER) analysis was performed to identify which species contributed most significantly to the observed differences in assemblage structure between the two habitats.

Results and Discussion

Comparison of wild bird assemblage characteristics

During the survey period, a total of 28 species (179 individuals) were observed in the restoration site and 30 species (156 individuals) in the forest, indicating a similar scale of occurrence between the habitats (Table 2). However, the overall Shannon–Weaver species diversity index (H') was significantly higher in the forest (3.07) than in the restoration site (2.38), suggesting a more even occurrence of diverse species in the forest.

Seasonal comparison of assemblage characteristics revealed that the forest maintained relatively stable richness (17-20 species), abundance (83-109 individuals), and diversity (H'=2.51-2.68) across all four seasons. In contrast, the restoration site exhibited lower richness (12-16 species), abundance (71-101 individuals), and diversity (H'=1.59-1.99) compared to the forest, with a pronounced difference in richness and diversity, suggesting that the occurrence was concentrated in a few species. This result is attributed to the restoration site's simple and open vegetation structure in its early stage, making it unstable for the habitation of diverse birds.

The foraging guild analysis showed a distinct difference in the utilization of foraging space between the two bird assemblages (Table 3). The mean abundance of GFs in the restoration site (36 individuals) was significantly higher than in the forest (21.25 individuals), although species richness was similar (4.25 vs. 4.50 species). This suggests that the simple vegetation structure and extensive grassland environment of the restoration site favored the habitation of GFs such as the tree sparrow (*Passer montanus*). Conversely, FG showed significantly higher richness (6.75 species) and abundance (34.75 individuals) in the forest

Table 3. Species richness and abundance of avian foraging guilds in restoration and forest

	Restoration		Forest	
	Richness	Abundance	Richness	Abundance
AF	0.75±0.96	2.50±4.36	0.00±0.00	0.00±0.00
AI	0.50±0.58	0.75±0.96	0.50±0.58	0.75±0.96
BF	1.00±0.82	1.50±1.29	3.00±0.00	4.50±1.00
FG	4.25±0.50	29.25±14.82	6.75±0.96	34.75±7.76
GF	4.25±1.50	36.00±20.61	4.50±1.29	21.25±8.46
OG	3.00±0.82	14.00±5.23	4.00±0.00	30.50±3.87
Total	13.75±1.71	84.00±12.46	18.75±1.26	91.75±12.04

Values are presented as mean±standard deviation.
AF, aquatic forager; AI, aerial insectivore; BF, bark/trunk forager; FG, foliage gleaner; GF, ground forager; OG, omnivore/generalist.

Table 4. PERMANOVA results for avian assemblages comparing restoration and forest

Factor	df	Sum of Sqs	R^2	F	*P*-value
Group	1	1.3281	0.2839	7.9291	0.001
Residual	20	3.3498	0.7161		
Total	21	4.6779	1		

PERMANOVA, permutational multivariate analysis of variance; df, degrees of freedom; Sqs, squares.

compared to the restoration site (4.25 species, 29.25 individuals). Furthermore, BFs, such as woodpeckers, were much more abundant in the forest (3 species, 4.50 individuals) compared to the restoration site (1 species, 1.50 individuals). These results show that the multi-layered forest structure functions as a stable habitat for birds by providing diverse foraging spaces and shelter, and they are consistent with previous studies indicating that the vertical structure of vegetation is closely related to the habitation of diverse bird species (Blinkova & Shupova, 2017; de Toledo *et al*., 2012).

Notably, AF were observed only in the restoration site (0.75 species, 2.50 individuals). This suggests that the wetlands and aquatic systems created by the restoration project function as novel habitats that are not found in the adjacent forest.

Comparison of assemblage structure between habitats

The PERMANOVA analysis revealed a statistically significant difference in the bird assemblage structure between the restoration site and the adjacent forest (*P*=0.001). Habitat type explained approximately 28.4% of the total bird assemblage variation (R^2=0.2839) (Table 4). This result was visually corroborated through the NMDS analysis (Fig. 3). The low stress value of the NMDS plot (0.1837846) indicates that the plot reliably represents the actual data distances (Clarke, 1993).

In the plot, the restoration site and the forest were

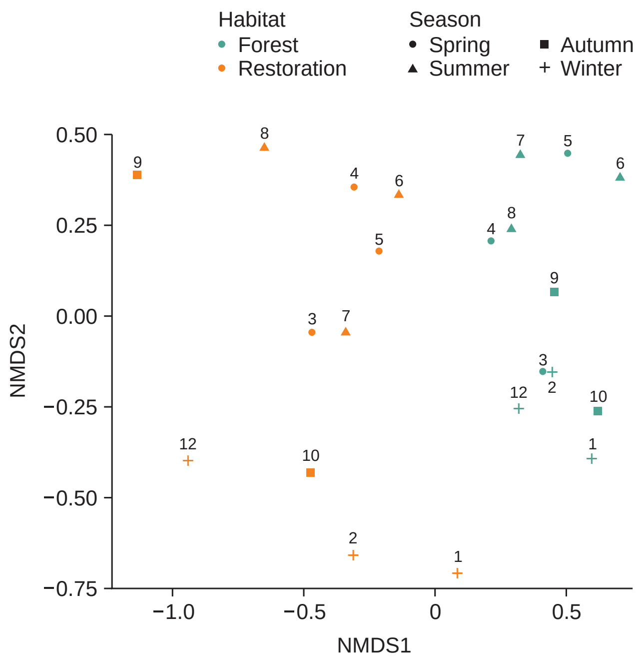

Fig. 3. Non-metric Multidimensional Scaling (NMDS) plot of avian assemblages comparing restoration and forest. Each point represents a sampling event, with numeric labels indicating the month of survey.

clearly separated into two groups along the horizontal NMDS1 axis, with the forest concentrated in the positive direction and the restoration site in the negative direction, showing the difference in bird assemblages based on habitat type. Notably, the restoration site samples were more dispersed compared to the relatively clustered forest samples, indicating the instability of the restoration assemblage, i.e., larger monthly and seasonal differences in assemblage structure.

SIMPER analysis was conducted to identify which species contributed most significantly to these differences (Table 5). The analysis showed that the difference in assemblages between the restoration site and the forest was largely contributed by the vinous-throated parrotbill (*Suthora webbiana*), tree sparrow (*Passer montanus*), azure-winged magpie (*Cyanopica cyanus*), oriental turtle dove (*Streptopelia orientalis*), and great tit (*Parus major*), in order of decreasing contribution. The top 10 contributing species accounted for approximately 77% of the total assemblage difference.

By comparing the average abundance (Group A [Restoration] vs. Group B [Forest]), *Suthora webbiana* (12.909 vs. 3.455) and *Passer montanus* (12.636 vs. 0.455) showed markedly higher occurrence in the restoration site, while *Cyanopica cyanus* (4.818 vs. 10.545), *Streptopelia orientalis* (3.727 vs. 8.000), and *Parus major* (0.364 vs. 5.545) had higher abundance in the adjacent forest. The adjacent forest provided a stable habitat for birds like *Parus major* that in the canopy and on branches. In this forest, breeding individuals and nests of species including *Parus major*, *Streptopelia orientalis*, and the black-naped oriole (*Oriolus chinensis*) were observed during the spring. Furthermore, the goldcrest (*Regulus regulus*), which primarily occurs in coniferous forests, was frequently observed from autumn to spring, highlighting the forest's function as a stable habitat. Conversely, in the restoration site, despite the planting of various food-providing species such as *Chionanthus retusus*, the occurrence of urban-adapted species like *Passer montanus* was concentrated, contributing most significantly to the difference from the forest assemblage. This dominance of urban-adapted species reflects biotic homogenization due to urbanization (McKinney, 2006), suggesting that the restoration site provides an environment favorable to urban-adapted species, distinct from the forest assemblage.

Furthermore, analysis of species exclusively observed in each habitat showed that water-dependent birds, such as the Eurasian teal, common kingfisher, and black-crowned night heron, were observed only in the restoration site. This highlights the effect of creating new habitat space in the isolated urban ecosystem. This aligns with prior research indicating that increasing landscape heterogeneity, such as creating water spaces in urban areas, positively influences bird species richness (Morgan *et al*., 2025). Conversely, species requiring multi-layered forest habitats and stable food sources, such as the black-naped oriole (*Oriolus chinensis*) and brown hawk-owl (*Ninox scutulata*), were founded only in the adjacent forest. This indicates that the adjacent forest performs a unique and crucial ecological function not offered by the restoration site, acting as a core habitat for disturbance-sensitive species.

Conclusion

This study found a statistically significant difference in the wild bird assemblage structure between the Mt. Sorasan urban ecological restoration site and the adjacent forest ecosystem. The complex, multi-layered structure of the adjacent forest was identified as a stable habitat for diverse birds. The restoration site, while in its early stage,

Table 5. Species contributions to avian assemblages dissimilarity based on SIMPER analysis

Top 10 contributing species	Avg. Contrib.	Contrib./SD	ava	avb	*P*-value	Cum. Contrib.
Suthora webbiana	0.112	1.036	12.909	3.455	0.206	0.154
Passer montanus	0.110	0.895	12.636	0.455	0.067	0.304
Cyanopica cyanus	0.085	1.518	4.818	10.545	0.007	0.421
Streptopelia orientalis	0.059	1.271	3.727	8.000	0.006	0.502
Parus major	0.054	1.907	0.364	5.545	0.001	0.577
Hypsipetes amaurotis	0.039	1.454	0.909	4.182	0.002	0.63
Pica pica	0.032	1.539	1.818	4.273	0.001	0.674
Regulus regulus	0.029	0.744	0.000	2.636	0.002	0.714
Aegithalos caudatus	0.022	0.901	0.545	2.091	0.094	0.744
Periparus ater	0.021	0.874	0.091	2.000	0.007	0.773

Avg., average; Contrib., contribution; SD, standard deviation; SIMPER, similarity percentages; ava, average abundance in Group A (Restoration); avb, average abundance in Group B (Forest); Cum, cumulative.

showed limitations in supporting the bird species found in the adjacent forest due to its open and simple vegetation structure. However, the restoration site also played a positive role by creating a previously lacking aquatic ecosystem in the surrounding area, providing a new habitat for water-dependent birds.

These results emphasize that the goal of ecological restoration should not be limited to simply increasing the area of green space. It should, from a long-term perspective, prioritize the creation of complex, multi-layered habitats that consider the process of ecological succession, and enhance connectivity with the adjacent natural ecosystem.

The Mt. Sorasan restoration site requires management to ensure that the planted trees can mature into a stable forest environment. Given that various food-providing plants have been already planted, it is expected that the site will facilitate the influx of diverse wild bird species from the adjacent forest and expand their habitat space in the future.

This study is significant because it empirically evaluated the effectiveness of an urban ecological restoration project through direct comparison with an adjacent natural ecosystem. The findings can be used as baseline data to present short-term restoration outcomes and the direction for long-term progress.

However, the study was limited to a short-term, one-year survey, and included only a single restoration site and its adjacent forest, precluding analysis of the influence of the surrounding landscape context and connectivity to the wider region. Future research is suggested to conduct long-term monitoring to track changes in bird assemblages following vegetation succession. It is also recommended to additionally investigate the influence of the landscape context surrounding the restoration site on bird communities.

Author Contributions

Conceptualization: TYC. Data curation: TYC, DK, HGM. Formal analysis: TYC, JC, HGM. Funding acquisition: JC. Investigation: TYC, HGM. Writing – original draft: TYC. Writing – review & editing: TYC.

Conflict of Interest

The authors declare that they have no competing interests.

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Appendix 1. Total species richness and abundance of avian assemblages in restoration and forest

Scientific name	Restoration				Forest				Foraging guild
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	
Acrocephalus orientalis	0	1	1	0	0	0	0	0	FG
Pica pica	4	2	1	2	5	6	6	8	OG
Oriolus chinensis	0	0	0	0	3	2	1	0	FG
Phasianus colchicus	0	0	0	0	1	1	0	0	GF
Phylloscopus inornatus	0	0	0	0	0	0	2	0	FG
Turdus naumanni	0	0	0	1	0	0	0	3	GF
Emberiza elegans	0	0	6	0	0	0	4	5	GF
Fringilla montifringilla	0	0	0	0	0	0	0	5	GF
Turdus hortulorum	0	0	0	0	1	1	0	0	GF
Phoenicurus auroreus	2	1	2	1	1	0	0	1	GF
Lanius bucephalus	0	0	2	1	0	0	0	0	FG
Streptopelia orientalis	10	4	3	5	9	17	6	14	GF
Cyanopica cyanus	12	11	8	4	14	18	18	15	OG
Alcedo atthis	0	0	1	0	0	0	0	0	AF
Eophona migratoria	0	0	8	4	0	0	8	4	GF
Parus major	1	2	1	0	5	5	10	9	FG
Chloris sinica	0	0	0	0	0	2	0	0	GF
Suthora webbiana	11	12	36	40	10	12	0	10	FG
Cuculus canorus	0	0	0	0	2	2	0	0	FG
Phylloscopus coronatus	2	0	0	0	6	0	0	0	FG
Regulus regulus	0	0	0	0	6	0	4	10	FG
Ninox scutulata	0	0	0	0	1	0	0	0	AI
Dendrocopos kizuki	1	3	0	0	2	2	2	2	BF
Poecile palustris	1	0	0	0	0	2	2	2	FG
Muscicapa dauurica	0	0	0	0	0	2	0	0	FG
Anas crecca	0	0	0	8	0	0	0	0	AF
Emberiza rustica	0	0	2	0	0	0	0	0	GF
Garrulus glandarius	0	2	0	0	2	5	2	1	OG
Aegithalos caudatus	2	0	0	2	3	0	8	6	FG
Dendrocopos major	0	0	0	1	1	3	1	1	BF
Hirundo rustica	2	1	0	0	0	0	0	0	AI
Hypsipetes amaurotis	2	4	0	4	5	6	3	8	OG
Periparus ater	0	0	0	1	6	0	5	4	FG
Passer montanus	31	57	0	5	0	2	0	0	GF
Picus canus	1	0	0	0	1	1	1	1	BF
Lanius tigrinus	0	1	0	0	0	0	0	0	FG
Eurystomus orientalis	0	0	0	0	0	2	0	0	AI
Nycticorax nycticorax	0	0	0	1	0	0	0	0	AF
Emberiza tristrami	0	0	0	2	0	0	0	0	GF
Total abundance	82	101	71	82	84	91	83	109	
Total species richness	14	13	12	16	20	19	17	19	

AF, aquatic forager; AI, aerial insectivore; BF, bark/trunk forager; FG, foliage gleaner; GF, ground forager; OG, omnivore/generalist.

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Spatial Distribution of *Bolboschoenus planiculmis* and Its Association with Daily Inundation Time in the Geum Estuary

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ABSTRACT

This study investigated the spatial distribution of the native halophyte *Bolboschoenus planiculmis* in the tidal wetlands of the Geum Estuary and analyzed its association with key hydrological factors. Based on drone imagery acquired in October 2024, a total of 1,344 patches were identified, covering a cumulative area of 13,754 m^2. These patches were primarily concentrated at an average distance of 351 meters from the terrestrial embankment. While over 74% of patch centroids were located within 15 meters of tidal creeks, multivariate logistic regression analysis indicated that proximity to creeks did not have a statistically significant effect on patch size ($P>0.05$). In contrast, average daily inundation duration (15.2-18.9 hours/day, mean 17.6 hours) showed a significant positive correlation with the formation of larger patches (odds ratio=1.75, $P<0.001$), suggesting that inundation regime is a key driver of patch development. The findings highlight the species' preference for mid- to lower-intertidal zones and underscore the importance of tidal and inundation management in formulating effective conservation and restoration strategies for halophytic plant habitats in estuarine ecosystems.

Keywords: *Bolboschoenus planiculmis*, Estuarine wetland, Geum Estuary, Inundation duration, Spatial distribution, Tidal creeks

Introduction

The Geum Estuary, where the Geum River meets the Yellow Sea, is a major estuarine ecosystem in Korea characterized by a wide tidal range and extensive mudflats (Kang *et al*., 2022). Since the construction of the Geum River estuarine barrage in 1990, water flow has been regulated, yet the area remains strongly influenced by tidal energy, resulting in the formation of a gently sloping intertidal landscape.

Bolboschoenus planiculmis (B. planiculmis), a perennial halophyte belonging to the Cyperaceae family, is widely distributed across East Asia, Central Asia, and Central Europe (Hroudová *et al*., 2009). This species typically grows to a height of 20-100 cm and is morphologically distinguished by its triangular stems and bifid styles, unlike the trifid styles of other Bolboschoenusspecies found in Europe (Hroudová *et al*., 2009). It exhibits strong clonal propagation ability, enabling survival under unfavorable conditions and rapid expansion when conditions improve (Oborny *et al*., 2012).

In East Asia, *B. planiculmis* functions as a key species in estuarine ecosystems, providing critical ecological services.

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Its tubers, formed at the ends of rhizomes, serve as an essential winter food source for endangered migratory birds such as the Siberian crane (Grus leucogeranus), the swan goose (Anser cygnoides), and various Cygnusspecies (Liu *et al*., 2016). Additionally, the species contributes to sediment stabilization and wave attenuation, facilitating soil retention and nutrient cycling in estuarine wetlands (IPCC, 2021; Yang *et al*., 2021).

However, populations of *B. planiculmis* have been declining globally due to habitat disturbances driven by climate change and human activities. In monsoon-dominated regions of East Asia, alterations in seasonal inundation regimes caused by embankment construction and land reclamation have significantly affected the survival and growth of this species (Yang *et al*., 2021). An *et al*. (2022) reported an optimal water depth range for *B. planiculmis* growth between 11.2 and 36.1 cm, with substantial reductions in growth observed under inundation conditions beyond this range.

Several studies have investigated the plant's tolerance to flooding. For instance, Yang *et al*. (2021) found that seasonal flooding supports better growth than continuous inundation, while Yang (2019) demonstrated high growth rates and photosynthetic efficiency at shallow water depths (0-5 cm). More recently, Park *et al*. (2024) revealed that *B. planiculmis* adjusts its biomass allocation between above- and below-ground structures to cope with flooding stress.

While the ecological importance of *B. planiculmis* in estuarine biogeochemical cycling is well documented, quantitative studies on the environmental determinants of its spatial distribution—particularly those focusing on large-scale patch formation—remain limited.

In a 2024 field survey, extensive patches of *B. planiculmis* were observed across the Geum Estuary, suggesting that the local hydrological environment may provide favorable conditions for its establishment and growth. Nevertheless, the specific environmental factors that shape this distribution, and the hydrological and geomorphological characteristics that favor its occurrence, have yet to be quantitatively assessed.

Therefore, this study aims to investigate the distribution characteristics of the large-scale *B. planiculmis* patches observed in the Geum River Estuary in 2024 and to identify the environmental factors determining these patterns. Specifically, this study seeks to address the following ecological questions: (1) Under what inundation conditions does *B. planiculmis* gain a competitive advantage? (2) What is the influence of spatial proximity to tidal creeks on patch establishment? To answer these questions, this study will: (1) quantify the precise spatial distribution and area of *B. planiculmis* patches through drone aerial photography; (2) measure key hydrological and topographical variables including water depth, daily inundation duration, and minimum distance to tidal creeks at each patch location; and (3) statistically analyze the relationships between these environmental factors and patch distribution and area.

This approach goes beyond simply describing distribution patterns; by quantitatively characterizing the habitat preferences of *B. planiculmis*, it enhances our understanding of the ecological niche of brackish-water halophytes and is expected to provide essential baseline data for future saltmarsh ecosystem conservation and restoration strategies. In particular, the findings from this study can be applied to identify key manageable hydrological variables (e.g., inundation time, drainage systems) in estuarine restoration projects and to predict changes in halophyte communities under sea-level rise scenarios associated with climate change.

Materials and Methods

Study area

The Geum Estuary, located at the confluence of the Geum River and the Yellow Sea, forms the boundary between Seocheon-gun in Chungcheongnam-do and Gunsan-si in Jeonbuk Special Self-Governing Province. The study area encompassed the section between the Geum River estuarine barrage and the Dongbaek Bridge, where large-scale patches of *B. planiculmis* are extensively distributed (Figs. 1, 2).

Data collection

Drone survey

High-resolution orthophotos were acquired using a Phantom 4 Pro V2 drone (SZ DJI Technology Co., Ltd., Shenzhen, China) in October 2024 across areas where *B. planiculmis* patches were densely distributed near the Geum River estuarine barrage. Flight missions were configured to achieve 80% image overlap, yielding 720 images at 150 m altitude.

Collected images were processed using Pix4DMapper software (Pix4D, Lausanne, Switzerland) following a standard photogrammetric workflow (initial alignment → point cloud generation → orthomosaic construction), resulting in georeferenced orthophotos with ~30 cm spatial resolution (Table 1). Geometric correction was performed using reference imagery from the National Geographic Information Institute (https://www.ngii.go.kr/) to minimize distortions from flight variations.

Environmental variable

Patch elevation and hydrological characteristics were derived from multiple sources (Table 1). Patch elevation data relative to mean sea level (MSL) were obtained from bathymetric surveys conducted by the Korea Hydrographic

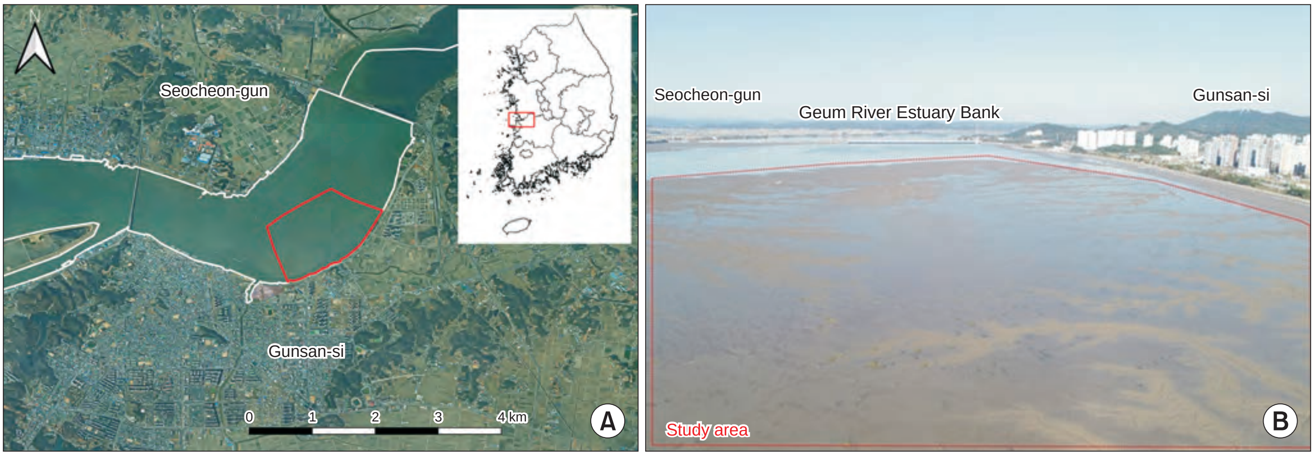

Fig. 1. Location of study area. (A) Map of study area. (B) Drone image.

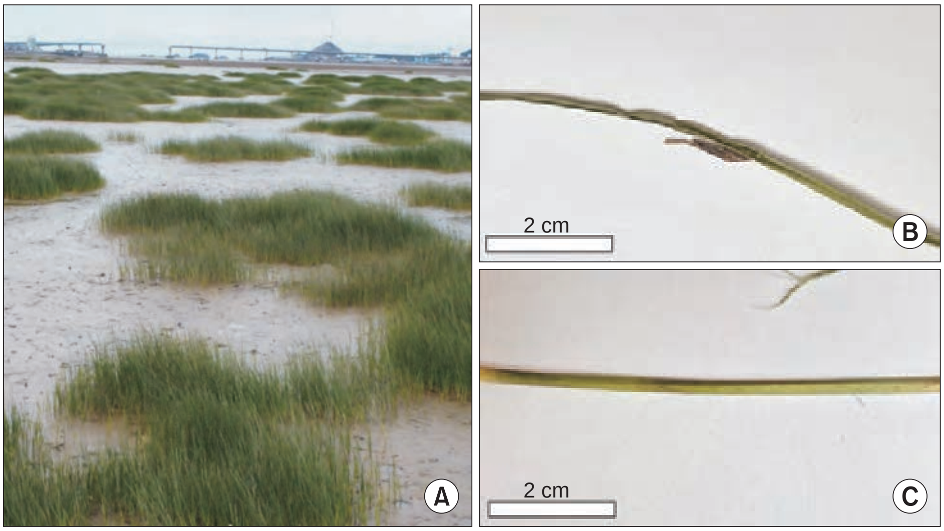

Fig. 2. Visual characteristics of *B. planiculmis* in the Geum Estuary. (A) Tidal flat patches formed by *B. planiculmis* colonies during low tide. (B) Spikelet of a collected specimen. (C) Triangular cross-section of the culm. *B. planiculmis*, *Bolboschoenus planiculmis*.

Table 1. Data sources and processing methods for environmental variables

Variable	Data source	Temporal/spatial resolution	Processing method
Patch area	Drone imagery (Phantom 4 Pro V2; SZ DJI Technology Co., Ltd., Shenzhen, China)	30 cm GSD, flight 150 m altitude, 80% overlap, fast mode	Pix4D Capture+orthomosaic (Pix4Dmapper; Pix4D, Lausanne, Switzerland)
Patch elevation	KHOA bathymetric data	Point data	Interpolated to patch centroids using nearest neighbor method
Tidal level	Janghang tide gauge (KHOA)	1-minute interval, June 2024	Converted to MSL
Inundation duration	Derived	Daily	Calculated from elevation+tidal data
Distance to creek	Digitized creek network	30 cm GSD (digitized creek network from drone orthomosaic)	Euclidean distance in QGIS

All spatial data were georeferenced to WGS84/UTM Zone 52N (EPSG:32652) with EGM96 geoid. Geometric correction was performed using NGII aerial reference imagery.
GSD, ground sampling distance; KHOA, Korea Hydrographic and Oceanographic Agency; MSL, mean sea level; QGIS, Quantum Geographic Information System; NGII, National Geographic Information Institute.

and Oceanographic Agency (KHOA) and interpolated to patch centroids using the nearest neighbor method in Quantum Geographic Information System (QGIS).

Tidal water level data at 1-minute intervals were acquired from the KHOA Janghang tide gauge station (Sinchang-ri, Janghang-eup, Seocheon-gun; N 36°00'25", E 126°41'15"), located approximately 5 km from the study site. All tidal elevations were referenced to MSL using the station's datum.

The spatial distribution, patch size, and number of *B. planiculmis* patches and tidal creeks were extracted from orthophotos using QGIS 3.4v.

Data analysis

To evaluate the relationship between *B. planiculmis* patch formation and hydrological conditions, a multivariate logistic regression analysis was performed. Daily inundation duration for each patch was calculated by combining patch elevation with 1-minute interval tidal water level records from June 2024:

Daily inundation duration (h day^{-1}) = [Σ(minutes when tidal level≥patch elevation)/60]/30, where tidal data consisted of 43,200 observations at 1-minute intervals over the 30-day period in June 2024 (n=30 days).

The dependent variable was binary: patches in the top 25% area quantile were classified as "large patches" (coded as 1), while all others were coded as 0. Independent variables included daily inundation duration (hours), minimum distance to tidal creeks (meters), and water depth (meters). All continuous variables were standardized (z-scores) for comparability.

Multicollinearity was assessed using the variance inflation factor (VIF). If VIF values exceeded 5 for multiple variables, the variable most strongly collinear with inundation time—namely, elevation—was excluded from the final model.

The final model was fitted using a generalized linear model with a binomial distribution and logit link function. Model performance was evaluated using the area under the curve (AUC) derived from 5-fold cross-validation. To assess spatial autocorrelation in model residuals, Moran's I statistic was calculated using the 10 nearest neighbors (k=10). Significant residual spatial dependence was detected, indicating the need for spatial correction (Dormann *et al*., 2007). Consequently, spatial eigenvector mapping (SEVM) was applied to account for spatial structure in the data (Griffith & Peres-Neto, 2006).

Result

Patch size and distance distribution

A total of 1,344 *B. planiculmis* patches were identified in the Geum Estuary. Patch sizes ranged from 0.52 m^2 to 79.06 m^2, with a mean of 10.23 m^2 and a standard deviation of 8.57 m^2. The cumulative area of all patches was 13,754 m^2 (Fig. 3). The distance from the terrestrial embankment (marking the boundary between land and intertidal zone) to patch centroids ranged from 163 m to 681 m, with an average of 351 m (Fig. 4). Notably, patch occurrence was most concentrated around 346 m from the embankment.

Distance to tidal creeks

The spatial relationship between patch centroids and tidal creeks is illustrated in Fig. 5. The minimum distance from patch centroids to the nearest tidal creek ranged from 0.1 m to 74.6 m, with a mean of 10.7 m, a median of 7.6 m, and a standard deviation of 10.3 m. In terms of distance categories: 517 patches (38.5%) were located within 5 m, 280 patches (20.8%) within 5-10 m, 199 patches (14.8%) within 10-15 m, 141 patches (10.5%) within 15-20 m, 96 patches (7.1%) within 20-25 m, 42

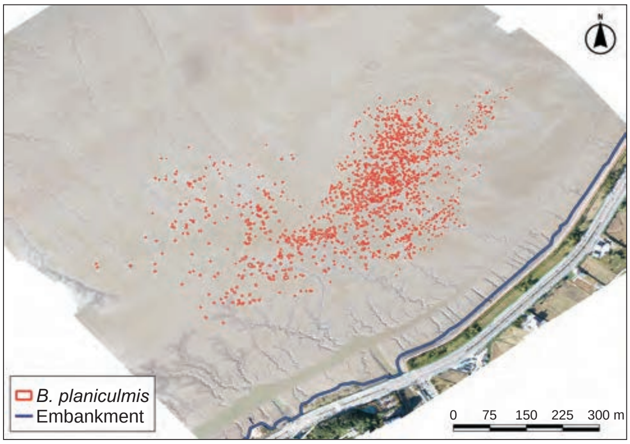

Fig. 3. Distribution of *B. planiculmis* patches (red) on the drone-derived orthomosaic; 1,344 patches totaling 13,754 m^2. *B. planiculmis*, *Bolboschoenus planiculmis*.

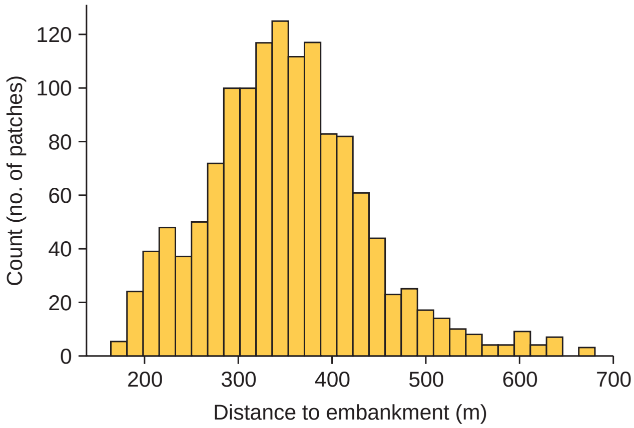

Fig. 4. Histogram of distances from patch centroids to the terrestrial embankment, highlighting a mode near 346 m.

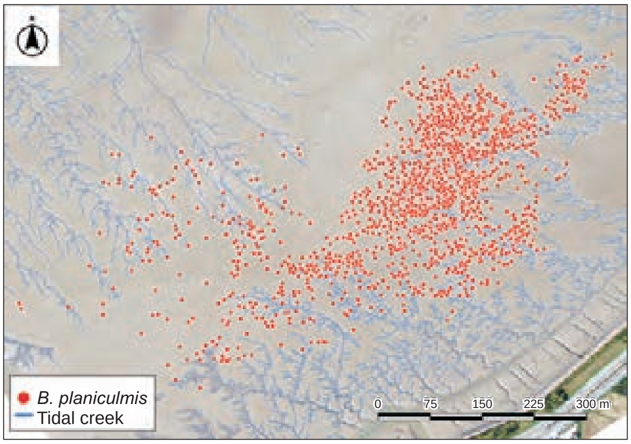

Fig. 5. Spatial relationship between patch centroids (red) and tidal creek (blue). *B. planiculmis*, *Bolboschoenus planiculmis.*

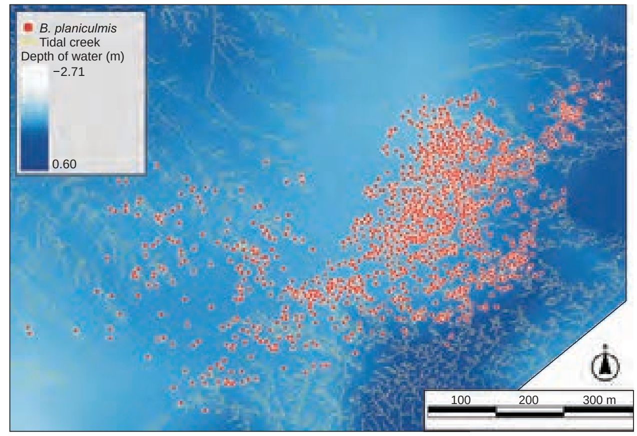

Fig. 7. Bathymetric map (MSL) overlaid with patch locations. MSL, mean sea level; *B. planiculmis*, *Bolboschoenus planiculmis.*

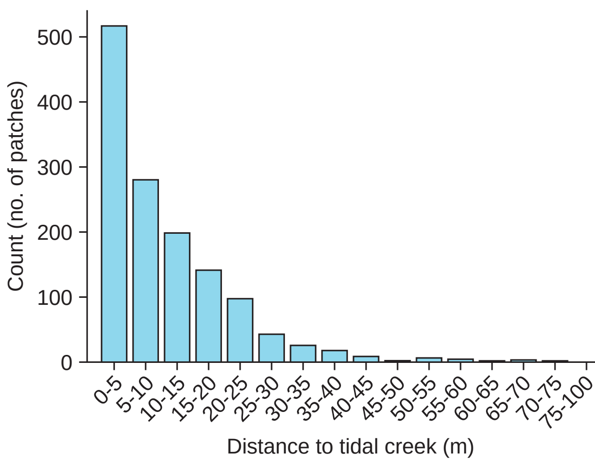

Fig. 6. Frequency distribution of minimum centroid-creek distances in 5 m bins; >74% within 15 m.

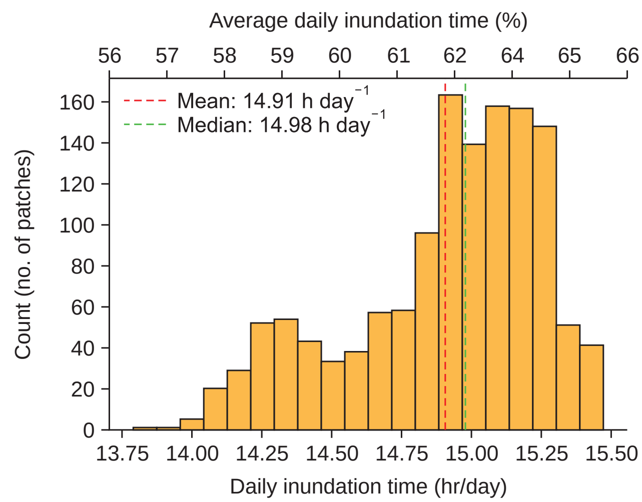

Fig. 8. Distribution of average daily inundation time (h day^{-1}) in July 2024 across patches.

patches (3.1%) within 25-30 m, 25 patches (1.9%) within 30-35 m, 18 patches (1.3%) within 35-40 m, and 26 patches (2.0%) were found beyond 40 m. Overall, more than 74% of patches were located within 15 m of a tidal creek, and over 90% were within 25 m (Fig. 6).

Bathymetry and inundation characteristics

The elevation (relative to MSL) of *B. planiculmis* patches ranged from −1.15 m to −0.44 m, with a mean of −0.91 m, a median of −0.92 m, and a standard deviation of 0.17 m (n=1,344; Fig. 7). Based on tidal records from June 2024, daily inundation duration ranged from 13.7 hours to 15.4 hours, with a mean of 14.9 hours, a median of 15.0 hours, and a standard deviation of 0.3 hours. Most values were concentrated between 14.7 and 15.2 hours per day (Fig. 8).

Statistical results

In the final multivariate logistic regression model, daily inundation duration and distance to tidal creeks were used as explanatory variables, while water depth was excluded due to multicollinearity. When water depth was included together with inundation duration and distance as candidate predictors, its VIF was 8,210, whereas VIFs for inundation duration and distance were both 1.09 (Table 2), indicating severe collinearity between depth and inundation.Inundation duration showed a significant positive association with the formation of large patches (top 25% area) (odds ratio [OR]=1.75, 95% confidence interval [CI]=1.51-2.05, P<0.001), indicating that a one-standard-deviation increase in inundation time increased the odds of forming a large patch by approximately 75%.

In contrast, the distance to tidal creeks was not a statistically significant predictor (OR=1.03, 95% CI=0.91-1.17, *P*=0.581) (Table 3). Model performance, as evaluated by 5-fold cross-validation, showed an average AUC of 0.624±0.030. Partial dependence analysis revealed that the predicted probability of large patch occurrence increased consistently with inundation duration, holding other variables at their median values (Fig. 9).

Additionally, Moran's I statistic indicated significant spatial autocorrelation in model residuals (Moran's I=0.028, *P*<0.05). However, after applying SEVM, residual spatial dependence was effectively eliminated (Moran's I=0.002, *P*=0.45), and model performance improved (AUC increased from 0.624 to 0.650).

Discussion

Key findings and ecological implications

This study quantitatively analyzed the relationship between the distribution of *B. planiculmis* patches and environmental variables in the Geum Estuary during 2024. A total of 1,344 patches were identified, covering an area of 13,754 m^2, indicating that the estuary provides favorable conditions for the establishment of this species. Notably, daily inundation duration emerged as a key determinant of patch size (OR=1.75, *P*<0.001), offering important insight into the species' ecological strategies.

The positive correlation between inundation duration and patch size suggests that *B. planiculmis* may possess a distinct ecological strategy compared to other halophytes. The observed mean inundation duration of 14.9 hours per day (13.7-15.4 hours), which accounts for approximately 62% of the day, represents a prolonged submersion period that is more extreme than the optimal depth range (11.2-36.1 cm) proposed by An *et al*. (2021). This implies either a high flood tolerance in the local population or a competitive advantage gained through suppression of other species under prolonged inundation.

Comparison with previous studies

The water depth range observed in this study (−1.15 m to −0.44 m) significantly deviates from the optimal range (5-10 cm) reported by Zheng *et al*. (2023). While this discrepancy may partly reflect differences in tidal datum or site-specific conditions, it also indicates that the ecological plasticity of *B. planiculmis* may be greater than previously recognized. Ma *et al*. (2024) reported that seasonal flooding is more favorable than continuous inundation; however, our findings show that *B. planiculmis* can successfully establish even under near-continuous inundation averaging 14.9 hours per day.

The lack of a statistically significant relationship between patch size and distance to tidal creeks (*P*=0.584)

Table 2. Multicollinearity diagnostics (VIF) for candidate predictors considered in the multivariate logistic regression

Variable	VIF
Depth*	8,210
Inundation	8,214
Distance	1.09

VIF, variance inflation factor.
*Depth showed severe multicollinearity with inundation (VIF>8,000) and was excluded from the final model.

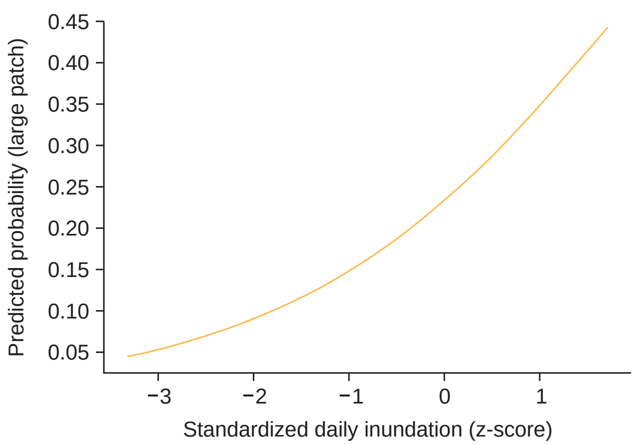

Fig. 9. Partial dependence of the predicted probability of large patches on inundation time with other covariates fixed at medians.

Table 3. Multivariate logistic regression for predictors of large *B. planiculmis* patches (top-quartile area)

Variable	Coef	OR	CI_low	CI_high	*P*-value*
Const	−1.18	0.30	0.27	0.35	<0.001
Inundation	0.56	1.75	1.51	2.05	<0.001
Distance	0.03	1.03	0.91	1.17	0.581

Coef: logistic regression coefficient (log-odds), OR: exp (coef). Continuous variables were standardized (z-score) prior to analysis, and ORs represent changes per 1 SD increase. Outcome: large patch (area ≥75th percentile)
B. planiculmis, Bolboschoenus planiculmis; OR, odds ratio; CI, confidence interval; SD, standard deviation; MSL, mean sea level; VIF, variance inflation factor; AUC, area under the curve.
*Wald test *P*-value.

was unexpected. Tidal creeks are generally thought to play important roles in seed and propagule dispersal, drainage, and nutrient input (Ma *et al*., 2024; Zheng *et al*., 2023). However, despite over 74% of patches being located within 15 m of a creek, no significant association with patch size was found. This suggests that, in the Geum Estuary, most patches may already lie within the influence range of creeks, rendering inundation duration a more dominant driver than creek proximity.

Spatial distribution and environmental gradients

The concentration of *B. planiculmis* patches at an average distance of 351 m (ranging from 163 m to 681 m) from the embankment, with peak density around 346 m, implies that this elevation zone within the intertidal gradient offers optimal conditions for establishment. Considering the findings of Park *et al*. (2024), which emphasize biomass allocation adjustment under flooding stress, this elevation may represent a balance point for optimal above- and below-ground growth.

The significant spatial autocorrelation detected in model residuals (Moran's I=0.028, P<0.05) suggests that patch formation is influenced not only by environmental variables but also by spatial processes. These may include local clonal expansion (Oborny *et al*., 2012) or spatial constraints on seed dispersal. The improved model performance after applying SEVM, with AUC increasing from 0.624 to 0.650, confirms the importance of incorporating spatial structure in species distribution modeling.

Limitations and future directions

Several limitations should be noted. First, this study is based on data from a single year and therefore does not capture temporal dynamics. Long-term monitoring is required to understand seasonal and interannual variability in *B. planiculmis* distribution. Second, the model's predictive power (AUC=0.624) remains moderate, suggesting that unmeasured variables such as soil characteristics, nutrient levels, interspecific competition, or disturbance frequency may also be influential. A more integrated modeling approach incorporating these factors is recommended.

Third, water depth was excluded from the final model due to high multicollinearity with inundation duration (VIF>5). Although this exclusion was statistically justified, it underscores the need for more refined hydrological indicators that consider tidal cycles in future studies. Fourth, this study focused on current patch distribution and did not directly assess initial colonization mechanisms or dispersal processes.

Conservation and management implications

The results of this study provide concrete guidance for the management of *B. planiculmis* habitats in the Geum Estuary. Patch size and establishment probability increased within the observed inundation window of 13.7-15.4 h day^{-1} (mean 14.9 hours), suggesting that maintaining a similar range of daily inundation duration during the growing season may enhance the stability of existing stands under the regulated hydrological regime of the estuarine barrage. In practice, barrage gate operations and environmental-flow releases should be configured so that key *B. planiculmis* zones are neither exposed for prolonged periods nor subjected to near-continuous flooding.

The spatial thresholds identified here can also be used to prioritize restoration and protection zones. Patches were concentrated in a mid-intertidal belt approximately 300-400 m seaward of the embankment and within 15 m of tidal creeks, providing practical criteria for selecting planting sites and evaluating the effects of dredging or construction projects. Because the tubers of *B. planiculmis* are an important food resource for migratory waterbirds and other wildlife (Liu *et al*., 2016), maintaining healthy stands through appropriate hydrological management may improve habitat quality for these species. At the same time, the potential impacts of rapid *B. planiculmis* expansion on mudflat structure and other halophytes should be monitored, and the inundation and spatial thresholds reported here can be used to limit further encroachment where necessary.

Conclusion

This study quantitatively demonstrated that the distribution of *B. planiculmis* patches in the Geum River Estuary is determined by two key environmental factors: inundation duration and distance to tidal creeks. Inundation duration was identified as the primary factor determining patch size and survival, with longer daily inundation periods significantly increasing the probability of patch establishment (OR=1.75, P<0.001). This finding provides crucial baseline data for understanding the ecological niche of brackish-water halophytes. Distance to tidal creeks was the key factor shaping the spatial distribution pattern of patches, with 74% of all patches located within 15 m of tidal creeks, suggesting that tidal creeks serve as primary conduits for seed and vegetative propagule dispersal.

Beyond these general patterns, the study identified specific hydrological and spatial thresholds—namely, an inundation window of approximately 13.7-15.4 h day^{-1} and a mid-intertidal belt 300-400 m seaward of the embankment and within 15 m of tidal creeks—that can be directly applied to habitat management and restoration planning. These thresholds offer practical guidance for designing barrage operation schemes, selecting restoration sites, and evaluating the potential impacts of future hydrological alterations.

Taken together, these findings can be used to predict and manage saltmarsh ecosystem changes under future climate change and anthropogenic disturbances. The large-scale *B. planiculmis* patches observed in the Geum River Estuary in 2024 represent a case of rapid ecosystem transformation that can occur when environmental conditions align with these two ecological characteristics (inundation tolerance and tidal-creek dependence). This highlights the dynamic nature of estuarine ecosystems and underscores the critical need for predictive, evidence-based, and adaptive ecosystem management strategies.

Author Contributions

Conceptualization: CY, JC. Formal analysis: CY. Investigation: CY, HYY. Methodology: CY. Supervision: JC. Visualization: CY. Writing – original draft: CY. Writing – review & editing: HYY, JC.

Conflict of Interest

The authors declare that they have no competing interests.

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Proposal of a Non-Invasive Research Approach Based on a Comparative Analysis of Field Surveys and Environmental DNA Studies in the Civilian Control Zone

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ABSTRACT

The Civilian Control Zone (CCZ) in South Korea is a highly restricted area with significant ecological value due to limited human access. This study explores the feasibility of non-invasive biodiversity monitoring using spider webs as environmental DNA (eDNA) collectors in the CCZ, particularly where traditional field surveys are constrained. A total of six spider webs were collected along the DMZ Peace Trail in Hwacheon-gun, Gangwon province, and subjected to eDNA metabarcoding using vertebrate-specific primers. Despite quality limitations in Q20 and Q30 scores, over two million reads were generated, and 531,429 high-quality reads were retained after filtering with the DADA2 pipeline. Taxonomic assignment using BLAST identified 13 vertebrate species, including nine mammals, two amphibians, and two birds. Comparative analysis with conventional field surveys revealed limited species overlap, but spider web eDNA successfully detected cryptic or rarely observed species, such as *Rattus norvegicus* and *Felis catus*. These findings suggest that spider web-derived eDNA offers potential as a complementary tool, especially in areas where direct observation is difficult or impossible due to safety or security concerns. However, incomplete reference databases and low detection efficiency highlight the need for improvements in sampling methods and local DNA libraries. This study presents a promising step toward developing alternative, non-invasive ecological monitoring techniques applicable to inaccessible terrestrial environments.

Keywords: Airbone environmental DNA, Civilian control zone, Non-invasive monitoring, Spider web eDNA, Terrestrial vertebrate monitoring

Introduction

The Civilian Control Zone (CCZ) is a buffer area extending 5 to 15 kilometers on either side of the ceasefire line that separates South and North Korea. Unauthorized access is strictly prohibited, and the absence of human activity has allowed the region to retain exceptionally high levels of biodiversity (Kim, 1997). Including the Demilita-

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rized Zone (DMZ), the area north of the CCZ accounts for only 1.13% of South Korea's total land area, yet supports approximately 4,315 species—representing 16.5% of the nation's known biodiversity (National Institute of Ecology [NIE], 2025).

The DMZ and CCZ, where natural forests have been preserved without human disturbance for over 70 years, represent critical regions whose study is essential for conserving and restoring the ecosystem of a unified Korea in the future. However, traditional biodiversity surveys in these areas face substantial difficulties, as the regions impose high risk to surveyors and are difficult to access due to security restrictions (Bak *et al.*, 2023). In particular, the CCZ surrounding the DMZ applies to both conditions, resulting in significant challenges for conducting surveys. Furthermore, depending on tensions between South and North Korea, surveyor access is frequently restricted.

Even when access is granted, only a small number of surveyors are permitted to enter under military supervision, and surveys are conducted with limitations in movement and time. Consequently, innovative research methods that can complement such restricted survey conditions are required.

Research employing environmental DNA (eDNA) originated from soil microbial community analyses, and, after becoming widely utilized in aquatic ecosystem studies, is now gradually expanding to terrestrial environments (Hassan *et al.*, 2022). For example, the invertebrate-derived DNA (iDNA) approach, which extracts DNA from blood-feeding invertebrates, allows the acquisition of DNA from various animals at a study site and provides species information for multiple taxa (Kocher *et al.*, 2017). This demonstrated that eDNA can detect organisms that cannot be found through traditional methods in harsh environments. eDNA is highly promising for future biodiversity monitoring because it offers strong species detection ability, requires relatively little effort, is non-invasive, does not require prior information on target species, and can be applied even in regions where traditional surveys are infeasible (Valentini *et al.*, 2016). Such advancements present the possibility of applying eDNA techniques to terrestrial ecosystems, with continuous methodological improvements underway.

Within this context of innovative research approaches, the use of spider webs as a new medium for eDNA collection has recently gained attention. Most spiders produce webs to capture prey for survival. Spider webs contain materials such as MaSp1, MaSp2, MaSp3, MaSp4, and MaSp5, resulting in adhesive properties (Peng *et al.*, 2024). These webs trap not only the organisms that spiders feed on but also various biological materials such as hair or body fragments from different species, enabling the extraction of diverse genetic material from this natural DNA filter (Gregorič *et al.*, 2022; Newton *et al.*, 2024). Recent studies have employed spider web samples to investigate multiple taxa (Newton *et al.*, 2024), suggesting the potential of spider webs as a non-invasive survey tool suitable for regions like the CCZ.

Research on collecting eDNA from the air has also advanced significantly. In one study, filtering airborne DNA at a zoo enabled detection of genetic material from 49 mammal and bird species. Another study collected airborne DNA in tropical rainforests and detected 71 bird species and 18 mammal species. These findings indicate that airborne eDNA can be used to monitor biological communities, and that spider webs can serve as an effective method for capturing such airborne DNA (Clare *et al.*, 2022; Lynggaard *et al.*, 2022).

As an alternative to address the challenges posed by the unique characteristics of the DMZ and CCZ, we propose a method for studying biodiversity using eDNA captured on spider webs.

Materials and Methods

Study site

eDNA samples were collected from six locations along the Baegamsan-Bimok trail of the DMZ Peace Trail, situated within the CCZ in Hwacheon-gun, Gangwon province, South Korea. Sampling sites were selected to spatially represent the broader landscape, and spider webs were visually located and collected while walking along the trail (Fig. 1).

Spider web collection

Spider webs were collected using sterile latex gloves. Each web was gently adhered to a GF/C glass microfiber filter (Whatman, Maidstone, UK) and then folded inwards so that the silk was enclosed. The folded filter was placed

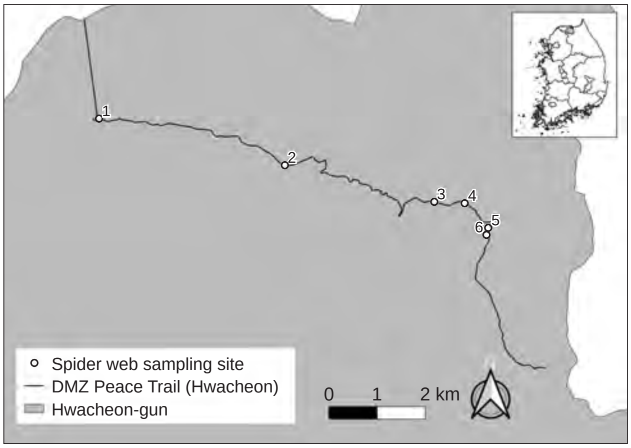

Fig. 1. Locations of spider web sampling along the DMZ Peace Trail in Hwacheon. DMZ, Demilitarized Zone.

into a sterile 50 mL conical tube. All tubes were transported to the laboratory at the NIE and stored at −20°C for one week to dry prior to DNA extraction.

DNA amplification and sequencing

Genomic DNA was extracted using the DNeasy Blood & Tissue Kit (QIAGEN, Hilden, Germany) according to the manufacturer's protocol. Extracted DNA was amplified using four primer sets targeting vertebrate mitochondrial markers (Table 1) (Riaz *et al.*, 2011; Taylor *et al.*, 1996; Ushio *et al.*, 2018; West *et al.*, 2021).

Amplified PCR products from each sampling site were pooled and submitted to Macrogen Inc. (Seoul, Korea) for next-generation sequencing using the Illumina MiSeq platform (paired-end 2×300 bp; Illumina, Inc., San Diego, CA, USA). Paired-end libraries were constructed during PCR amplification, and subsequent sequencing was conducted on the MiSeq platform.

Raw sequencing reads were processed using the DADA2 v1.28 pipeline implemented in R software ver 4.3.2 (R Foundation, Vienna, Austria; Callahan *et al.*, 2016). This pipeline enables the accurate inference of zero-radius operational taxonomic units (ZOTUs) through a series of quality control and denoising steps.

Initially, low-quality reads were filtered using the filterAndTrimfunction, which removes sequences that fall below quality score thresholds or fail to meet minimum length requirements. Following quality filtering, error rate models were constructed using the learnErrorsfunction, and high-resolution denoising was conducted with the dadafunction to infer exact amplicon sequence variants (ASVs).

Paired-end reads were then merged using the mergePairsfunction. Only successfully merged, non-chimeric sequences were retained. A final sequence table was generated using makeSequenceTable, and chimeric reads were removed using the removeBimeraDenovofunction.

The resulting dataset comprised ZOTUs suitable for downstream taxonomic assignment and ecological analyses.

All high-confidence ZOTUs were queried against the National Center for Biotechnology Information (NCBI) nucleotide database using basic local alignment search tool (BLAST). Taxonomic identification was assigned to the species level if the sequence identity was ≥99%. Sequences with 97-99% similarity were reported as sp. within the corresponding genus.

Comparison with field surveys

To evaluate the feasibility of spider web eDNA as a non-invasive tool, sequencing results were compared with traditional field survey data. Field observations conducted in the same season and region were sourced from the NIE's 2025 biodiversity survey report of the CCZ (NIE, 2025).

Results

Environmental DNA sequencing outcomes

eDNA extracted from spider webs collected at six sampling points yielded a total of 2,000,944 sequencing reads, corresponding to 602,284,144 base pairs (Table 2), which was sufficient for downstream analyses. However, overall Q20 and Q30 quality scores were suboptimal, prompting sequence trimming using the DADA2 pipeline. A sharp quality drop was observed after 160 bp, and trimming was accordingly performed at this position. Following the full DADA2 workflow, a total of 531,988 reads representing 880 unique sequences were retained.

Sequences with fewer than 10 reads were excluded from further analysis under the assumption that they were likely derived from non-specific amplification or sequencing errors. After this filtering step, 789 sequence variants comprising 531,429 reads were subjected to BLAST searches using the NCBI nucleotide database.

Among the BLAST results, only 169,495 reads could be confidently assigned to taxa with ≥97% identity. Most of the classified reads were attributed to mammals, fol-

Table 1. Metabarcoding primer sets for spider web samples

Name	Target taxa	Sequence information	Length of target sequence (bp)	Reference
16Smam1	Mamalian	5'-CGGTTGGGGTGACCTCGGA-3'	130	Taylor *et al.* (1996)
16Smam2		5'-GCTGTTATCCCTAGGGTAACT-3'		
16SRep1	Reptile	5'-AGACNAGAAGACCCTGTG-3'	245	West *et al.* (2021)
16SRep2		5'-CCTGATCCAACATCGAGG-3'		
12S-V5	Vertebrate	5'-CTAGAGGAGCCTGTTCTA-3'	98	Riaz *et al.* (2011)
12S-V5		5'-TTAGATACCCCACTATGC-3'		
MiBird	Bird	5'-GGGTTGGTAAATCTTGTGCCAGC-3'	239	Ushio *et al.* (2018)
MiBird		5'-CATAGTGGGGTATCTAATCCCAGTTTG-3'		

Table 2. Summary of eDNA extraction and sequencing results

Sample ID	Total bases (bp)	No. of reads	GC content (%)	AT content (%)	Q20 (%)	Q30 (%)
Spweb1	109,673,564	364,364	44.8	55.2	53.7	45.9
Spweb2	82,574,534	274,334	45.2	54.8	55.5	48.0
Spweb3	88,909,982	295,382	45.6	54.4	58.3	50.9
Spweb4	117,520,032	390,432	46.1	53.9	54.4	46.9
Spweb5	98,614,222	327,622	46.0	54.0	54.7	47.3
Spweb6	104,991,810	348,810	45.9	54.1	57.4	50.1

eDNA, environmental DNA.

lowed by fungi, plants, birds, and amphibians (Fig. 2). For the purposes of this study, only reads corresponding to mammals, birds, and amphibians were retained; those matching plants, bacteria, or human DNA were excluded as non-target sequences.

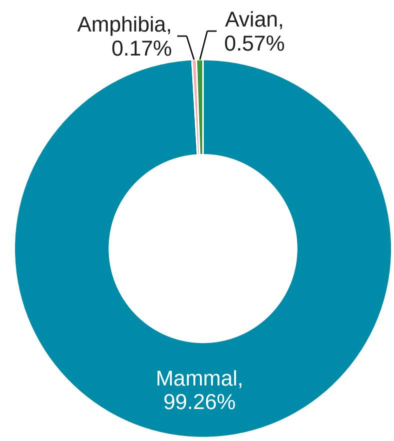

Fig. 2. Composition of three major biological groups identified by environmental DNA metabarcoding.

Field survey results

A traditional biodiversity field survey was conducted along the Baegamsan-Bimok trail in the CCZ region of Hwacheon-gun, Gangwon province, South Korea. The survey identified 12 mammal species (three orders, eight families), 41 bird species (10 orders, 23 families), and nine amphibian and reptile species (three orders, eight families) (NIE, 2025). Two additional direct surveys had previously been conducted in the DMZ Peace Trail Hwacheon section during 2022 and 2024. In 2022, due to access restrictions during the spring, the survey was limited to two to three seasons. This resulted in the identification of 16 mammal species (five orders, 10 families, 16 genera), 45 bird species (nine orders, 26 families, 35 genera), and 12 amphibian/reptile species (three orders, seven families, nine genera). In 2024, access was granted only during the spring, yielding a one-season survey in which 13 mammal species (four orders, nine families, 11 genera), 41 bird species (10 orders, 23 families, 31 genera), and nine amphibian/reptile species (three orders, eight families, seven genera) were documented.

Comparison between eDNA and field survey results

In 2024, due to heightened tension between South and North Korea, only one entry into the CCZ was permitted. Field survey results from this single entry were compared with the eDNA results. eDNA extracted from spider webs collected at six sites along the field survey route revealed 13 species in total: nine mammal species belonging to three orders and seven families, two bird species belonging to one order and one family, and two amphibian species belonging to one order and two families.

The Baegamsan-Bimok course of the DMZ Peace Trail was previously referred to as the Hwacheon course of the DMZ Peace Trail, and the only prior eDNA-related study was conducted by the Ministry of Environment (2023), which analyzed eDNA collected from water. Thus, no comparative dataset exists for eDNA research using spider webs. However, when direct survey results were compared with the indirect survey results obtained from spider webs, four mammal species—*Hydropotes inermis*, *Sus scrofa*, *Naemorhedus caudatus*, and *Sciurus vulgaris*—were congruent between the field survey and eDNA results, and all bird and amphibian species detected through eDNA were also species confirmed through the direct field survey.

Among the five mammal species detected only through eDNA and not in the field survey, four species—*Felis catus*, *Canis lupus familiaris*, *Bos taurus*, and *Capra hircus*—are taxa that are currently excluded from assessments in natural ecosystem surveys (Table 3).

Discussion

Environmental DNA analysis results

More than 2,000,000 reads of eDNA extracted from spider webs were identified, confirming that a considerable amount of genetic material adheres to spider webs. However, due to the characteristics of eDNA, in which

Table 3. List of vertebrate species identified from eDNA collected on spider webs

Taxa	Scientific name	Percent identity (%)	No. of reads
Mammal	*Hydropotes inermis*	100	10,289
	Felis catus	100	64
	Canis lupus familiaris	100	14
	Sus scrofa	100	191
	Naemorhedus caudatus	100	8,273
	Bos taurus	100	22,050
	Capra hircus	100	313
	Rattus norvegicus	100	8,144
	Sciurus vulgaris	100	7,027
Amphibia	*Bombina orientalis*	100	14
	Dryophytes japonicus	100	85
Avian	*Sittiparus varius*	100	271
	Parus major	100	52

eDNA, environmental DNA.

Table 4. Comparison of eDNA studies in South Korea

Research category	Research environment	Sample type	Target taxa	No. of detected species	Advantage	Limitation	Reference
Current study (eDNA/ spider web)	Restricted terrestrial area (CCZ)	Spider web	Mammals, birds, amphibians	13	Applicable in restricted access areas	Lack of reference DB (especially limits ASV identification)	Current study
Aquatic system (eDNA)	Restricted aquatic area (CCZ)	Freshwater	Fish	71	Applicable in restricted access areas	Need to check NCBI genetic information	Eum *et al.* (2023)
Terrestrial (spider web)	Near agricultural land	Spider web	Invertebrates (arthropods)	4	Can identify both the spider and its prey through the cobweb	Difficult to distinguish between prey and eDNA	Kim and Kim (2024)

eDNA, environmental DNA; CCZ, Civilian Control Zone; ASV, amplicon sequence variant; NCBI, National Center for Biotechnology Information.

Q20 and Q30 values are not sufficiently high (Xu *et al.*, 2015), the number of final usable reads was reduced. This suggests the possibility that the eDNA in the samples was partially degraded or contaminated due to the nature of the material.

Crucially, the DADA2 pipeline, which is highly stringent, was applied not only for quality filtering but also for the removal of technical artifacts. The marked reduction in the number of final reads (from 2,000,944 to 531,988) was a deliberate consequence of excluding sequences that were likely derived from sequencing errors, low quality, and, importantly, chimeric sequences (false hybrids formed during PCR). This rigorous technical filtering ensures that the resulting ASVs are highly accurate and reliable for downstream analysis (Berard *et al.*, 2025; Bylemans *et al.*, 2018).

As is commonly observed in metabarcoding studies using universal vertebrate primers—especially when applied to complex substrates such as airborne eDNA—the initial taxonomic assignments in this study also included a substantial proportion of non-target taxa. These consisted primarily of fungi and plants, which were likely co-amplified due to the broad-binding properties of universal primers rather than reflecting true biological abundance. For the purpose of vertebrate-specific biodiversity monitoring, these sequences, along with those corresponding to bacteria, archaea, and human DNA, were excluded to enhance taxonomic precision. The resulting filtered dataset, which retained only high-confidence vertebrate assignments, is summarized in Fig. 2.

In this study, eDNA from mammals was detected at notably high levels. This is presumed to be due to their high activity levels and the large amount of eDNA generated through shedding hair, saliva, territorial marking, and defecation. Additionally, because the number of mammal species in the Korean ecosystem is relatively small, genetic research on these species has been more active, likely ensuring a sufficient number of reference sequences required for BLAST analysis. It is expected that if genetic studies on domestic species become more extensive in the future, re-analysis of the present results may be possible.

Comparison with field survey results

When comparing the field survey results with the eDNA results, only a very limited amount of information was obtained relative to the field survey. Therefore, research on the CCZ using eDNA from spider webs was determined to be insufficient as a replacement for field surveys. However, its applicability appears to be high for small rodents and other taxa that are difficult to study in field surveys due to the necessity of traps or reliance on sensor cameras. In Table 3, *Rattus norvegicus*, a small rodent, is a species that is extremely difficult to visually observe in the field and rarely appears along human movement paths. Species with such ecological traits may be effectively studied using eDNA.

In particular, mammals—with abundant genetic references due to ongoing genetic research and which disperse eDNA through territorial marking, defecation, activity, and shedding—may be especially suited for complementary research using this method.

Additionally, the field survey detected *Prionailurus bengalensis*, one of the endangered species in Korea. This species is typically surveyed in the field through feces and footprints. However, in the eDNA results, spider webs collected near feces attributed to *P. bengalensis* contained DNA of *F. catus*, not *P. bengalensis*. Since the two species leave similar footprints and fecal characteristics, this is presumed to be an error in field-based trace identification. Therefore, eDNA research using spider webs is considered an appropriate method to complement such trace-based surveys. In this context, previous research in South Korea has successfully applied spider web eDNA to identify spider species and their prey in agricultural ecosystems (Kim & Kim, 2024), demonstrating the method's viability in domestic settings. A comparison of representative eDNA studies conducted in South Korea, including the present study, is summarized in Table 4 (Eum *et al.*, 2023; Kim & Kim, 2024). However, the objectives and technical challenges of the present study differ substantially. Whereas the earlier study focused on invertebrate detection and food web analysis, our research targeted vertebrate species in a highly restricted terrestrial environment. The successful detection of mammals, birds, and amphibians via spider web eDNA in the CCZ represents the first such attempt in South Korea. This pioneering application demonstrates the potential of spider web eDNA as a conservation tool for biodiversity monitoring in inaccessible or ecologically sensitive areas.

Limitations in species-level identification

Another result observed in this study is that most of the final eDNA sequences could not be accurately identified to the species level and were discarded. Among the 531,988 sequences obtained, only about 30% (169,495 sequences) were successfully matched via BLAST, which suggests a high likelihood that the data included DNA from species whose genetic information has not yet been studied. This may indicate that the lack of genetic information for Korean species currently limits the accuracy of eDNA analyses, highlighting the need for expanding genetic databases of domestic species in the future.

Conclusion

In the case of the DMZ and CCZ in Korea, these areas represent ecological repositories that preserve natural environments in their original form due to restrictions imposed for safety and national security. Although many researchers wish to access these regions for scientific investigation, entry is strictly controlled because of national security and safety concerns. Since active research cannot be conducted under conditions of limited time, limited access, restricted survey areas, and safety risks, this study was carried out as an effort to compensate for such limitations by referring to preceding studies conducted abroad. Overseas, eDNA has been applied to deep-sea environments, estuarine water-quality monitoring, and soil assessments, and is also considered applicable to fields such as ancient organism detection, plant–pollinator interactions, diet analysis, invasive species monitoring, pollution, and air-quality assessments (Ruppert *et al.*, 2019).

However, unlike the substantial sequence data reported in many foreign studies, this study obtained only a limited amount of sequencing data. This is attributed to the fact that access was restricted in 2024 due to heightened tensions between South and North Korea, resulting in a single survey opportunity; that this was the first attempt using spider webs, leaving issues such as optimal DNA extraction methods and standardized spider-web collection procedures insufficiently developed; and that genetic reference data for Korean species are lacking. These limitations must be addressed and improved.

Rather than demonstrating a fully established detection method for eDNA, the present study indicates the potential of eDNA-based approaches as a supplementary strategy for terrestrial ecological surveys in regions such as the DMZ, where direct field investigations pose risks to researcher safety and raise national security concerns. To improve future research efficiency and accuracy, the following enhancements are suggested. First, criteria for spider-web collection and related methodologies should be developed through diversified research efforts to improve data quality. Second, reference databases must be expanded by establishing genetic barcodes and genomic information for Korean species to increase species-identification accuracy in BLAST analyses. Finally, a collaborative system with the military should be established. To enable regular and stable sample collection in the DMZ and CCZ, a system in which personnel such as scientific military units collect spider-web samples on site should be developed.

This study represents a case demonstrating the potential of eDNA–based biodiversity surveys even in regions with restricted access, such as the DMZ. With systematic and periodic sample collection and expansion of genetic reference data, this approach may be developed into a practical and effective supplementary research tool in the future.

Author Contributions

Conceptualization: SJE. Data curation: SJE, NK, HJK, JK. Formal analysis: SJE, NK. Funding acquisition: NK. Writing – original draft: SJE, NK. Writing-review & editing: SJE, NK.

Conflict of Interest

The authors declare that they have no competing interests.

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Review Article is expected to be focused discussion of defined topics relevant to the scope of PNIE. General remarks are same with original article. Manuscripts include a title page (with a running title), abstract and keywords, text, author contributions, conflicts of interest, acknowledgments, funding, references, tables, and figures. Abstract should be written in English within 150 words in one paragraph. The text can be written in free style. The review articles should be submit- ted in the same way as regular papers and received the same review process.

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Research and Publication Ethics

PNIE PROCEEDINGS OF THE NATIONAL INSTITUTE OF ECOLOGY OF THE REPUBLIC OF KOREA

Enacted August 5, 2020
Revised July 26, 2022
Revised June 23, 2025

The *Proceedings of the National Institute of Ecology of the Republic of Korea* (PNIE) adheres to the ethical guidelines for research and publication described in Guidelines on Good Publication (http://publicationethics.org/resources/guidelines), the International Committee of Medical Journal Editors (ICMJE) Guidelines (http://www.icmje.org), and Principles of Transparency and Best Practice in Scholarly Publishing (http://doaj.org/bestpractice). PNIE follows the international standards for editors and authors press release, https://publicationethics.org/resources/international-standards-for-editors-and-authors and the Committee on Publication Ethics (COPE) flowcharts, https://publicationethics.org/resources/flowcharts.

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Editor's & Reviewer's Guide

Enacted August 5, 2020
Revised June 23, 2025

Editor's Guide

Editors have the following responsibilities:

♦ To acknowledge receipt of submitted manuscripts within a few days of receipt and to ensure the efficient, fair and timely review process of submitted manuscripts.

♦ To ensure that submitted manuscripts are handled in a confidential manner, with no details being disclosed to anyone, with the exception of the referees, without the permission of the author, until a decision has been taken as to whether the manuscript is to be published.

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Principles of Transparency and Best Practice in Scholarly Publishing

PNIE PROCEEDINGS OF THE NATIONAL INSTITUTE OF ECOLOGY OF THE REPUBLIC OF KOREA

Enacted October 26, 2022
Revised June 23, 2025

1. Name of Journal

The official journal title is *Proceedings of the National Institute of Ecology of the Republic of Korea*. Abbreviated title is PNIE.

2. Website

i. The URL address of official journal website is https://accesson.kr/pnie/.

ii. 'Aims and Scope' statement

It aims to promote, but is not limited to, the achievements of basic ecological research conducted at home and abroad. The prospective audience is researchers conducting global collaborative research as well as ecological studies in the Asia-Pacific region. The scope is not only basic ecological research on terrestrial and aquatic populations, communities, ecosystems and landscapes but also applied issues such as data science and climate change based on ecological research.

iii. Readership

For those who study basic ecological studies of terrestrial and aquatic populations, communities, ecosystems and landscapes, as well as those who study applied ecology such as climate change and data science based on ecological studies. Its readership can be expanded to other positions: • Researchers can obtain the latest topics in domestic and international ecological research; • Professors can access and adopt a variety of data for education; • Students can understand the latest trends in ecological research at home and abroad; • Policy makers can reflect the results of the papers in international ecological research policies.

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