



# 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, sub-alpine 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 ser-

vice 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 red-line 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 (%).

**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 → Biodiversity 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.

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 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
Urban/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

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 socio-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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