Nature Conservation

Nature Conservation 55: 21–39 (2024)
DOI: 10.3897/natureconservation.55.113483

Research Article

Environmental characteristics, including soil and vegetation composition, in relation to the occurrence patterns of an endangered lizard, *Eremias argus*, in a fluvial island, South Korea

Eunhee Cho[1], Deokjoo Son[1]

1 *Department of Science Education, Dankook University, Yongin-si, 16890, Yongin, Republic of Korea*
Corresponding author: Deokjoo Son (djson0714@dankook.ac.kr)

Abstract

Eremias argus, known as the Mongolian racerunner, is a reptile that has been designated as a level II endangered species in South Korea since 2005 despite being listed as "Least Concern" by the International Union for Conservation of Nature. Particular vegetation and soil characteristics are critical components of the habitat of *E. argus*, which is an ectotherm. However, research on the environmental characteristics of *E. argus* living on a fluvial island is lacking. This study sought to characterize the soil environmental factors and vegetation composition of *E. argus* habitats on Doriseom Island, South Korea by dividing the island into an area in which *E. argus* occurred frequently (F zone) and an area in which *E. argus* occurred rarely (R zone). Both soil hardness and cobble cover were significantly higher in the R zone (soil hardness: 1.6 ± 0.2 kg·cm^{-2}, mean ± standard error; cobble cover: 40 ± 5%) than in the F zone (soil hardness: 0.9 ± 0.1 kg·cm^{-2}; cobble cover: 18 ± 3%). Plant litter cover did not differ significantly based on *E. argus* occurrence. The vegetation composition within F and R zones appeared distinct, though *Coreopsis lanceolata* dominated both zones. A sand dune sedge, *Carex pumila*, thrived in F zone sites, where soil hardness was low, while the endemic *Aster danyangensis*, which prefers cobble areas, was found largely in the R zone. In conclusion, *E. argus* was most commonly found in areas with low soil hardness dominated by dune vegetation. Understanding endangered species' habitat requirements can provide important clues for establishing conservation plans and restoration measures.

Key words: Cobble cover, conservation, Mongolian racerunner, reptile, soil hardness

OPEN ACCESS

Academic editor: Md Mizanur Rahman
Received: 29 September 2023
Accepted: 16 January 2024
Published: 30 January 2024

ZooBank: https://zoobank.org/6E6354D4-A58E-4C6B-9BEC-7323067B3F09

Citation: Cho E, Son D (2024) Environmental characteristics, including soil and vegetation composition, in relation to the occurrence patterns of an endangered lizard, *Eremias argus*, in a fluvial island, South Korea. Nature Conservation 55: 21–39. https://doi.org/10.3897/natureconservation.55.113483

Introduction

The Intergovernmental Panel on Climate Change (IPCC) has stated that endangered species are at risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other factors, such as habitat modification (Doherty et al. 2020), over-exploitation (Auliya et al. 2016), environmental pollution (Gibbons et al. 2000), and invasive species (Dueñas et al. 2021). Specifically, a considerably larger percentage of amphibians and reptiles are at risk compared to birds or mammals (Cordier et al. 2021; IUCN 2023). Although reptiles are important members of food chains and play pivotal roles in maintaining ecosystem dynamics (Ali et al. 2018), reptile populations have experienced serious declines worldwide (Chang et al. 2022), and approximately 20% of reptile species are considered threatened (IUCN 2023).

Eremias argus, known commonly as the Mongolian racerunner, is a small lacertid lizard in the family Lacertidae. The species has a body length of 150–200 mm, including the tail, and has a limited distribution in the Korean Peninsula, Mongolia, China, and Russia (Park et al. 2014). It is known as a specialist that generally occupies grassy sand dunes and riverbanks with little vegetation (Park et al. 2014). *Eremias argus* has been designated as a level II endangered species by the Ministry of Environment in South Korea since 2005 (Song et al. 2013), although it is listed as Least Concern by the International Union for Conservation of Nature (IUCN) (Orlova et al. 2019). In South Korea, *E. argus* populations are suffering a sharp decline because of habitat loss, degradation, and fragmentation resulting from coastal sand dune development (Kim et al. 2012b). In addition, *E. argus* populations in South Korea exhibit genetic fragmentation, indicating limited movement of individuals between subpopulations even when subpopulations are geographically close to one another (Park et al. 2014). In light of the *E. argus* populations' restricted range within Korea, Mongolia, China, and Russia, it is evident that the long-term viability of the species hinges on the conservation and restoration of its native habitats in these countries.

Globally, several studies on *E. argus* have been conducted, including research into the species' population genetics (Zhao et al. 2011), metabolism (Chen et al. 2016), herbicide sensitivity (Wang et al. 2021), and reproductive strategy (Sun et al. 2013). Within South Korea, studies considering population genetics (Park et al. 2014), mating behavior (Kim et al. 2012a), population size (Song et al. 2013; Chang et al. 2021), habitat distribution (Do et al. 2022), and food resources (Jeong and Song 2010) have been conducted. While extensive studies have been conducted on the coastal sand dune and mountain habitats of *E. argus* (Kim et al. 2011; Kim et al. 2012b), research into the species' habitat environment, such as the vegetation structure and soil characteristics, on a fluvial island remains notably limited.

The effectiveness of conservation programs targeting endangered species relies heavily on a comprehensive understanding of these species' specific habitat needs (Souter et al. 2007). Environmental characteristics are the result of interactions between biotic and abiotic factors, such as those relating to soil, vegetation, and microorganisms; these factors are highly interrelated and each is important to habitat formation (Reynolds et al. 2003). Soil properties are significantly influenced by certain environmental factors such as climate, topography, parent materials, vegetation, and disturbance due to human activity (Chen et al. 1997; Bakhshandeh et al. 2014; Cazzuffi et al. 2014). In particular, plant roots influence soil slope stability and erosion processes by impacting both hydrological processes and the geomechanical structure of the soil (Cazzuffi et al. 2014). In addition, plant roots alter their local environment in a number of ways, from modifying the soil's biophysical, chemical, and mechanical properties, to stimulating microbial abundance and diversity, ultimately reinforcing soil mechanically (Stokes et al. 2014). The physical characteristics of soil, such as its hardness and porosity, are largely influenced by vegetation (Huang et al. 2007) and can impact the burrowing choices of different lizard species (Zaady and Bouskila 2002; Zeng et al. 2016). In addition, the growth and regenerative capacity of vegetation can be significantly affected by soil compaction (Amrein et al. 2005). Furthermore, external disturbances can exacerbate soil compaction in a positive feedback loop when direct compaction destroys vegetation cover (Garden et al. 2007). For reptiles in particular, vegetation and soil are crucial components of species' habitat requirements, underscoring the significance of understanding these factors.

The goal of this study was to characterize the vegetation composition and soil environmental factors of *E. argus* living on the fluvial island, Doriseom Island, in South Korea. Because many elements constitute a habitat, this study was conducted by measuring not only abiotic factors such as soil hardness, cobble cover, and plant litter cover, but also biotic factors such as vegetation composition. We then compared how these environmental components differed between areas where *E. argus* individuals are common and areas where they are rare.

Methods

Study site

This study was conducted from May to November 2022 on Doriseom Island (37°13'34.6"N, 127°43'17.9"E), which is located in Yeoju-si, Gyeonggi-do, South Korea. Doriseom Island is a fluvial island at the confluence of the Namhangang River and the Cheongmicheon Stream (Fig. 1a, b). The island is approximately 906 m in length at its longest point, approximately 520 m wide, and has an area of approximately 292,370 m^2. During the nearly 30 years from 1991 to 2020, the average annual temperature on Doriseom Island was 11.7 °C, and the average annual precipitation was 1,315.9 mm (KMA 2023). Doriseom Island has an entirely flat terrain formed by the accumulation of alluvial soil approximately 5 m above the surface of the Namhangang River and the Cheongmicheon Stream (National Geographic Information Institute 2021). There is no river running through the interior of the island, and during major floods in the summer, the entire island can be affected by flooding. There are no inhabitants and houses, although some researchers visit the island to study the plants and animals.

Doriseom Island is a valuable and unique habitat, particularly for the resident reptile *Eremias argus* and flowering plant *Aster danyangensis*, both of which are classified as endangered wildlife class II by the Ministry of Environment (Macias et al. 2021). However, anthropogenic activities such as a river maintenance project have led to habitat reduction, which has been identified as a major threat to *E. argus* (Macias et al. 2021).

We first recorded the distribution of *E. argus*, which largely occurs in the southwest of Doriseom Island (86 sites) and is rarer in the northeast (10 sites; Fig. 1c). We then used the frequency of *E. argus* occurrences to divide Doriseom Island into two zones: a zone in which *E. argus* frequently occurs in the southwest (F zone) and a zone in which *E. argus* rarely occurs in the northeast (R zone; Fig. 1d).

Vegetation survey

The vegetation survey to identify plant community structure was conducted by randomly installing 1 m × 1 m quadrats (*n* = 138; 78 in the F zone and 60 in the R zone) in Doriseom Island from May to November 2022. In each quadrat, the plant cover (%) was surveyed and recorded in 5% increments, and plant species

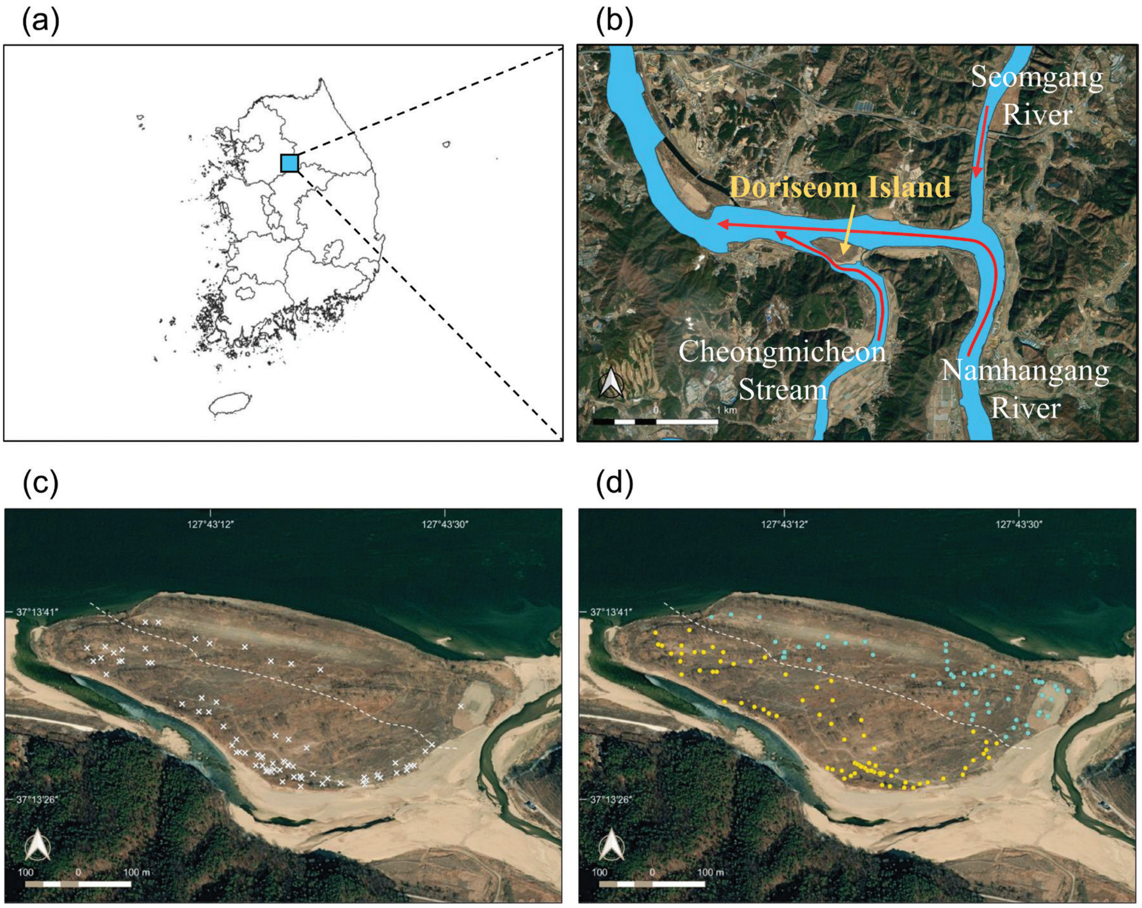

Figure 1. Location of *Eremias argus* study sites on Doriseom Island **a** location of the survey site on a map of South Korea **b** Doriseom Island is at the confluence of the Namhangang River and the Cheongmicheon Stream **c** the 96 sites where *E. argus* was found are indicated with white cross symbols (Bing Maps, working with QGIS 3.22.16) **d** the zones where *E. argus* occurred frequently (frequent zone, hereafter F zone) and rarely (rare zone, hereafter R zone) were determined. F zone sites are marked with yellow points (n = 78), while R zone sites are marked with mint-colored points (n = 60). At each point, the vegetation composition and soil environmental factors were surveyed.

were identified using various references (Lee 2003; Park 2009). In addition, we classified the observed plants into exotic and native plants. The nomenclature followed the "World Flora Online" (https://wfoplantlist.org/plant-list), the "Korea Biodiversity Information System Database" (http://www.nature.go.kr/main/Main.do) and Korea National Arboretum (2022).

Measurement of environmental factors

Three environmental factors were measured: soil hardness (kg·cm^{-2}), cobble cover (%), and plant litter cover (%). Soil hardness was measured with five randomly selected replicates in each quadrat using a pocket penetrometer (Forestry Suppliers, Inc., 77114, Jackson, United States), and an average value of soil hardness was calculated from the five replicates. If the soil was covered with cobbles and it was impossible to measure soil hardness, soil hardness was recorded as 4.5 kg·cm^{-2}, which was the maximum value of the soil hardness gauge (measurement range 0.01–4.5 kg·cm^{-2}). Like the plant cover, the cobble and plant litter covers (%) were recorded in 5% increments within each quadrat.

Data analysis

All statistical analyses were performed using R statistical software ver. 4.2.1 (R Core Team 2022) and the vegan (Oksanen et al. 2022), lawstat (Gastwirth et al. 2020), and ggplot2 (Wickham 2016) packages.

First, to identify significant differences in vegetation composition between the F zone and the R zone, we performed a permutational multivariate analysis of variance (PMAV) with the "adonis" function from the vegan package using Bray–Curtis distance (Oksanen et al. 2022). Standard deviational ellipses ("ordiellipse" function) were plotted in the NMDS ordination to describe zone site compositional differences. Species cover values were log-transformed (log(cover + 1)) to minimize the influence of rare plant species (Májeková et al. 2016). To examine how the dominant plant species differed between the two zones, we performed a rank-sum analysis. The percent cover of plant species in each quadrat was summed and each species' total sum of cover was sorted in descending order and visualized in a rank sum plot. In addition, native and exotic species richness and the percent cover of *Coreopsis lanceolata*, which was the dominant plant species in Doriseom Island, were compared using a *t*-test. Prior to the *t*-test, homogeneity of variance was tested through the "levene.test" function in the lawstat package (Gastwirth et al. 2020). In addition, the environmental factors (soil hardness, cobble cover, and plant litter cover) were compared between F and R zones using a *t*-test analysis for equal variances and Welch's test for heteroscedasticity (Zimmerman and Zumbo 1993; Burns 2006).

Second, non-metric multidimensional scaling (NMDS) was performed to elucidate the relationship between vegetation composition and the environmental factors (soil hardness, cobble cover, and plant litter cover) using the "metaMDS" and "envfit" functions from the vegan package (Oksanen et al. 2022). In addition, vegan's "ordisurf" function was used to visualize the gradient of environmental factors (soil hardness, cobble cover, and plant litter cover) in the NMDS ordinations.

Results

Vegetation composition

In a vegetation survey, 69 species belonging to 47 genera within 18 families were observed: Poaceae (25 species, 36%), Asteraceae (9 species, 13%), Cyperaceae (6 species, 8%), and other families (Appendix 1). Exotic plant species, including ecosystem-disturbing species designated by the Korean Ministry of Environment, accounted for approximately 42% of the total flora and were represented by 29 species. There were 27 species of plants common to both F and R zones, as well as 23 species found only in the F zone and 19 species found only in the R zone. For example, the dune sedge *Carex pumila* was found only in the F zone, while *Aster danyangensis*, which thrives in cobble environments, was found only in the R zone.

Coreopsis lanceolata showed an overwhelmingly high total cover in both zones (F zone: 2,771%, R zone: 1,571%; Fig. 2). Of the 20 plant species with the highest total percent cover, *C. lanceolata*, *Carex pumila*, and *Artemisia indica* had the highest percent cover in the F zone, while *C. lanceolata*, *Themeda triandra*, and *A. indica* had the highest percent cover in the R zone.

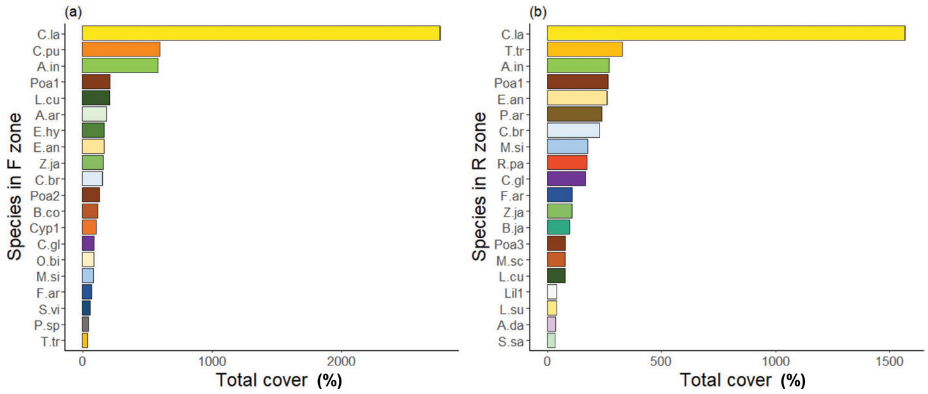

Figure 2. Rank-sum plot showing the sum of the total cover of plant species within the surveyed quadrats **a** F zone (n = 78) and **b** R zone (n = 60). Only the top 20 cover values for each zone are shown. Species are ordered from most abundant to least abundant. Abbreviations indicate plant species names, and the full species name is provided in Appendix 1.

Table 1. Species richness and average cover of *Coreopsis lanceolata* according to the frequency of *Eremias argus* occurrence in F and R zones. SE, standard error. *, significant difference (p < 0.05).

Index	F zone (n = 78)		R zone (n = 60)	
	Mean	SE	Mean	SE
Total plant richness	4.7*	0.2	4.0	0.2
Native species richness	2.5*	0.2	2.1	0.2
Exotic species richness	2.2	0.1	2.0	0.2
Cover of *Coreopsis lanceolata* (%)	36*	3	26	3

Native plant richness in the F zone (2.5 ± 0.2, mean ± standard error) was significantly higher than that in the R zone (2.1 ± 0.2; Table 1). On the other hand, exotic plant richness was 2.2 ± 0.1 in the F zone and 2.0 ± 0.2 in the R zone, representing no significant difference. *C. lanceolata* average cover was 36 ± 3% in the F zone and 26 ± 3% in the R zone. *Coreopsis lanceolata* was the dominant species in the two zones, but its percent cover was significantly higher in the F zone (p < 0.05).

Relationship between vegetation composition and soil environmental factors

In the comparison of communities using Bray–Curtis distance, the vegetation composition in F and R zones differed significantly according to the frequency of *E. argus* occurrence (PMAV; F = 4.28; p = 0.001; r^2 = 0.03), although the r^2 value is very low. An NMDS was performed to elucidate the relationships between vegetation and soil environmental factors in Doriseom Island (stress value = 0.186). As a result, all three environmental factors (soil hardness, cobble cover, and plant litter cover) had a significant effect on the vegetation composition (p < 0.05; Fig. 3). In addition, as soil hardness increased, the amount of plant litter (such as dead plant leaves and twigs) on the surface tended to decrease.

Soil hardness showed a positive relationship with *C. lanceolata* (C.la) and *Metaplexis japonica* (M.ja), but was negatively correlated with *A. indica* (A.in) and *Fallopia dumetorum* (F.du), which were related with low plant litter cover.

Cobble cover was positively correlated with *Galium verum* subsp. *asiaticum* (G.ve) and *Populus nigra* (P.de), but showed a negative correlation with *Ambrosia artemisiifolia* (A.ar) and *Miscanthus sinensis* var. *purpurascens* (M.si).

Comparison of soil environmental factors

We compared soil environmental factors according to the frequency of *E. argus* occurrence and found significant differences in soil hardness and cobble cover. Soil hardness was 0.9 ± 0.1 kg·cm^{-2} in the F zone and significantly higher at 1.6 ± 0.2 kg·cm^{-2} in the R zone (p < 0.05; Fig. 4a). Particularly, a significant difference was observed in cobble cover, which was 18 ± 3% in the F zone and 40 ± 5% in the R zone (p < 0.01; Fig. 4b). On the other hand, plant litter cover was 59 ± 3% in the F zone and 49 ± 5% in the R zone, being statistically similar regardless of the frequency of *E. argus* occurrence (p > 0.05; Fig. 4c).

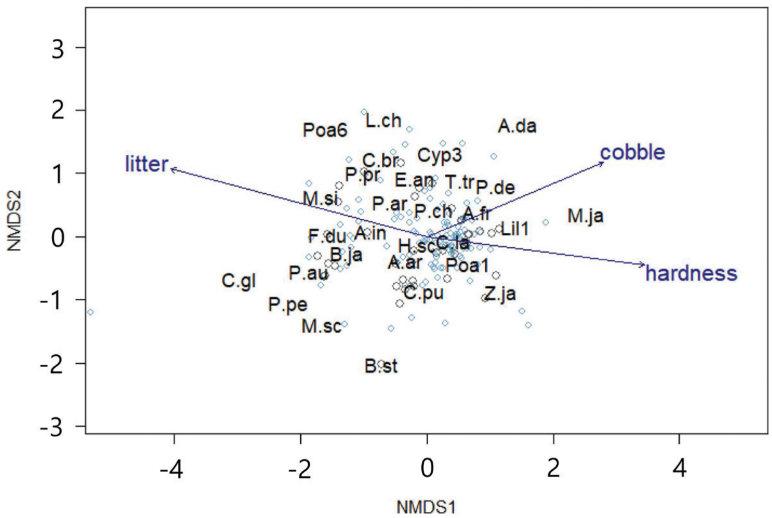

Figure 3. Non-metric multidimensional scaling (NMDS) plot representing the relationships between vegetation composition and soil environmental factors (stress value = 0.18). Plant cover data were log-transformed (log(cover + 1)), and raw, untransformed environmental factor data were used. Abbreviations indicate plant species names, and the full species name is provided in Appendix 1. Blue points indicate the surveyed quadrats, and grey points indicate rare plant species. The vectors with blue arrows show significant soil environmental factors (p < 0.05).

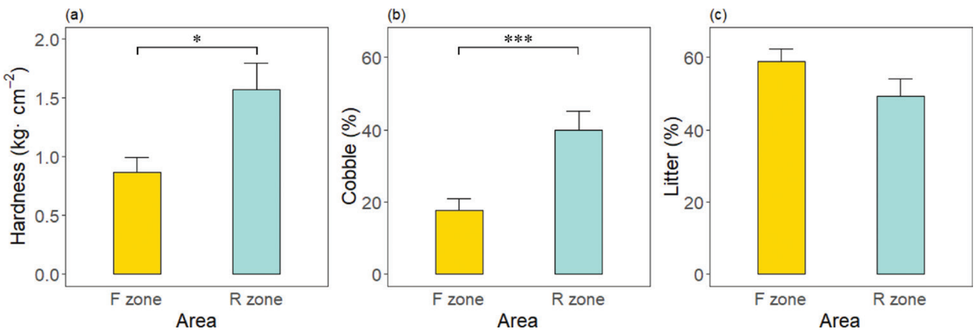

Figure 4. Differences in soil environmental factors (soil hardness, cobble cover, and plant litter cover) according to the occurrence patterns of *Eremias argus*. The yellow bar represents the zone with a high frequency of *E. argus* (F zone, n = 78), and the mint-colored bar represents the zone where *E. argus* is rare (R zone, n = 60). Differences in **a** soil hardness **b** cobble cover, and **c** plant litter cover between these two zones were considered. Standard errors are shown as error bars, and signs above the bars indicate whether the values differ from two zones (* p < 0.05, *** p < 0.001).

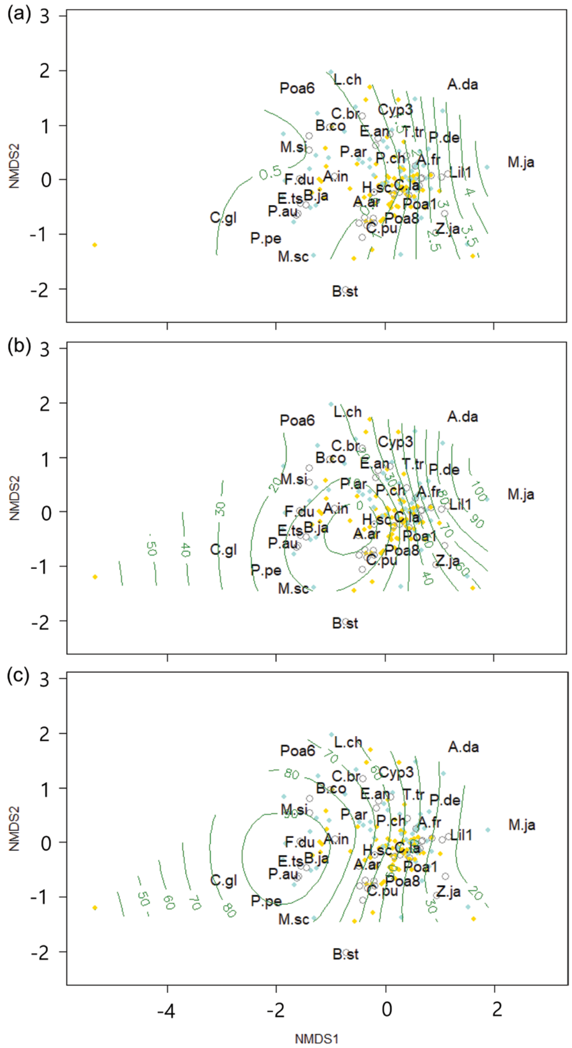

Figure 5. NMDS representation of the relationship between soil environmental factors and surveyed areas based on *Eremias argus* occurrence patterns. The yellow points indicate the zone with a high frequency of *E. argus* (F zone), and the mint-colored points indicate the zone where *E. argus* was rare (R zone). Differences in **a** soil hardness **b** cobble cover, and **c** plant litter cover between these two zones were considered. Additionally, the "ordisurf" function from the vegan package was used to separate the range of environmental factors with green lines.

Soil hardness ranged between 0.5–2 kg·cm^{-2} in most quadrats regardless of the frequency of *E. argus* occurrence, but high hardness values (2 kg·cm^{-2} or more) were more common in the R zone ($p < 0.05$; Fig. 5a). Cobble cover ranged from 0 to 40% in most areas, but values above 70% appeared only in the R zone ($p < 0.001$; Fig. 5b). Plant litter cover was similar in both zones ($p > 0.05$; Fig. 5c).

Discussion

Given the wide variation in *E. argus* occurrence within Doriseom Island, we divided the island into two zones based on the frequency of *E. argus* occurrence and examined how the two areas differed in terms of vegetation composition and soil physical environment. *Eremias argus* frequently appeared in areas with lower soil hardness and less cobble cover.

Vegetation composition

According to the vegetation survey on Doriseom Island, *Coreopsis lanceolata*, *Artemisia indica*, and *Erigeron annuus* were dominant in both F and R zones, but there were slightly significant differences in species composition. In the F zone, the percent cover of *Carex pumila* and *Ambrosia artemisiifolia* was high, while in the R zone, grasses such as *Themeda triandra*, *Phalaris arundinacea*, and *Miscanthus sinensis* var. *purpurascens*, as well as a Korean endemic plant, *Aster danyangensis*, showed high percent cover (Fig. 2).

The most dominant herbaceous species on Doriseom Island, *C. lanceolata*, was positively correlated with soil hardness (Fig. 3). However, *C. lanceolata* was more abundant in the F zone, where the soil hardness was lower than that in the R zone, indicating that this species was widely distributed throughout the island. Compared to the R zone, which was mostly covered with cobbles and had high soil hardness, the F zone, in which *E. argus* was more common, had some sandy soil with low soil hardness. In addition, plant richness and native plant richness was higher in the F zone than in the R zone, where the soil hardness was especially high. High soil hardness can obstruct plant growth for several reasons (Unger and Kaspar 1994), including hindrance of root penetration (Singh et al. 2015), low soil water retention (Ngo-Cong et al. 2021), and reduced soil aeration (Watson and Kelsey 2006).

Generally, *C. lanceolata* readily adapts to diverse ecosystems such as cut slopes, roads, and riverbanks (KIE 2018). It is also known to thrive in a wide range of climates, from temperate to subtropical (Batianoff and Halford 2002). *Coreopsis lanceolata* is native to the eastern United States and is considered a potentially serious weed in temperate to subtropical regions of Australia (Batianoff and Halford 2002). In addition, it is listed as one of Japan's 100 most noxious invasive plants (Arifin and Okamoto 2023). This plant species limits the light available to native vegetation (Arifin and Okamoto 2023) and spreads from the approximately 12,000 seeds produced each flowering season (Zeng et al. 2014) or by vegetative growth (Batianoff and Halford 2002). In the future, it will become necessary to monitor how quickly *C. lanceolata* will spread in Doriseom Island.

Other species that demonstrated high cover in both the F and R zones were *A. indica* and *E. annuus*, which were generally distributed across Doriseom Island. *Artemisia indica* and *E. annuus* are typical pioneer species, dominating areas shortly after a disturbance (Pacanoski 2017). This pattern suggests that Doriseom Island frequently experiences disturbances such as periodic flooding and human visits.

Unlike *C. lanceolata*, *A. indica*, and *E. annuus*, a few species, like the sedge *C. pumila*, exhibited a particularly high percent cover in areas with relatively low soil hardness in the range of 1.0–1.5 kg·cm^{-2} (Fig. 5a). *Carex pumila* is a typical dune plant that thrives in sandy soil with low hardness (Burgess 1984). This plant can be seen in the coastal sand dunes of Sinduri in South Korea, which is the habitat for the Mongolian racerunner, *E. argus*, (Lee et al. 2020), mirroring our findings. *Carex pumila* is also found in the coastal sand dunes of southern South Korea and Jeju Island (Oh and Kim 2008). Therefore, *E. argus* and *C. pumila* appear to inhabit similar environments.

On the other hand, certain species were rarely found in the F zone but were common in the R zone. This pattern was especially true of *A. danyangensis*. This plant is endemic to South Korea, growing in limited areas of the Namhangang River basin, and is listed as a class II endangered species by the Ministry of Environment (Kim et al. 2022). *A. danyangensis* was especially abundant in the R zone and exhibited a strong positive correlation with cobble cover. More specifically, *A. danyangensis* only thrived in areas where cobble cover exceeded 80% (Fig. 5b). *A. danyangensis* typically inhabits riverside gravel sandbars, creating a shaded environment when the gravel and cobble remain unembedded and exposed on the surface (Lee et al. 2017). This microenvironment is known to be an important factor in the germination and establishment of *A. danyangensis* seedlings (Kagaya et al. 2008). In fact, an alternative habitat was created to restore the population of *A. danyangensis* in the eastern part of the R zone. Since the surface of the alternative habitat was covered with cobbles with a diameter of about 7 cm or more, the frequency and cover of *A. danyangensis* is judged to have a large positive relationship with cobble.

In general, herbaceous species dominate Doriseom Island, but woody and shrub species such as black poplar (*Populus nigra*), black locust (*Robinia pseudoacacia*), and indigo bush (*Amorpha fruticosa*) are becoming more common. Menke (2003) reported that a number of lizard species that occupy grassland habitats are threatened by the invasion of woody bushes. Therefore, the environmental condition of *E. argus* living on Doriseom Island may also be threatened by the expanding tree population. In addition to trees, river flooding and human visits represent disturbances on Doriseom Island. Garden et al. (2007) found a positive correlation between the presence of native reptiles and a moderate level of weed cover, ranging from 25% to 50%, indicating that the structure offered by vegetation (e.g., refuge) may be more important than vegetation composition for lizard habitat. These findings support those of Pinto et al. (2018) who noted that on a micro-habitat level, the likelihood of reptile presence, as well as their abundance and species diversity, grew as plant diversity increased. On the other hand, Jellinek et al. (2004) reported that overall lizard species richness was negatively associated with increased plant cover. The relationship between reptiles and vegetation can vary greatly depending on the species (Scott et al. 2006; Mizsei et al. 2020). Some reptiles prefer habitats with dense vegetation for a variety of reasons, including the vegetation's role in offering shelter and protection from adverse conditions (Attum et al. 2006), refuge from predators (Sato et al. 2014), and reproduction sites (Martin and Murray 2011). Moreover, unlike in our study, *E. argus* have been found to be more abundant in areas with dense vegetation, preferring the warm thermal environment of denser habitats (Zeng et al. 2016). Consequently, generalizing about the significance of plant cover for all reptiles is challenging.

Soil environmental characteristics for *E. argus*

Our result establishing that the areas where *E. argus* frequently appeared had a low cobble cover and low soil hardness is consistent with the findings of previous studies, which have shown that reptiles are absent from environments with high soil compaction (Garden et al. 2007). Individuals in one coastal dune region consistently utilized the grass dune habitat throughout the year, using it even for hibernation (Kim et al. 2012b). *Eremias argus* is most commonly found in areas with low soil hardness that are dominated by dune vegetation, which is similar to *E. argus* habitat in South Korea (Song et al. 2013; Lee et al. 2020). Since sand dunes are typically arid environments known for their very low solidity (Zaady and

Bouskila 2002), they are preferred by *E. argus*, which lay eggs on the ground. Female *E. argus* lay around six eggs in a minimum of two batches, typically from late May to early July in South Korea (Kim et al. 2012a). Soil surface resistance, measured in this study as soil hardness, has been understood as important in burrow site selection for some burrowing lizards (Souter et al. 2007). Although lizards' preferred habitats may vary slightly, generally, habitats must provide essential areas for foraging, hiding, hibernation, egg-laying, and mating (Kim et al. 2012b).

Eremias argus is known as a specialist in dune areas (Park et al. 2014). However, habitat specialists are most likely to become locally extinct because they are rarely able to adapt to drastic habitat changes (Cordier et al. 2021). Furthermore, Doriseom Island is likely to be affected by habitat changes due to human activities and riverside development, resulting in changes in animal movement patterns (Doherty et al. 2021).

Environmental management strategies for *E. argus*

Vegetation composition and soil environment were found to differ according to the frequency of *E. argus* occurrence. However, several predominant plant species were ubiquitously distributed throughout Doriseom Island, and soil environment, especially soil hardness and cobble cover, may affect vegetation structure. In previous research conducted by Souter et al. (2007), no specific vegetation structure was found to be correlated with lizard occupancy within grassland habitats, but potential for soil type to influence the plant community was found. Carpio et al. (2017) also indicated that a more diverse herbaceous ground cover, containing a greater variety of species and resembling natural vegetation, would offer a better solution for promoting diversity in reptile assemblages within agricultural landscapes. Because specific plant species are less important for reptile habitats than the physical conditions that they create, a broader array of habitats, such as a combination of open spaces in close proximity to vegetation cover, can fulfill the requirements of a habitat with diverse structure (Edgar et al. 2010).

Coreopsis lanceolata, an exotic plant that is expanding and forming uniform patches across Doriseom Island, poses a potential threat to the habitat of *E. argus*. As the climate crisis intensifies, it facilitates the spread of invasive exotic species, which in turn changes the composition of native communities (Vilà et al. 2011). Some have also reported that when the average annual temperature rises by 1 °C, invasive exotic plants become better competitors; in addition, it is known that when invasive exotic species dominate a specific ecosystem, species diversity decreases and a highly homogenized community is created (Kortz and Magurran 2019; Mathakutha et al. 2019). Moreover, negative relationships have been observed between exotic plant cover and lizard species abundance and diversity (Jellinek et al. 2004). Hence, it is crucial to persistently monitor and conduct follow-up research regarding the proliferation of *C. lanceolata* on Doriseom Island.

Ecotones—the transitional zones between habitats such as sunny woodland edges, grassland-scrub interfaces, and interfaces within grasslands of varying vegetation heights—are especially important for reptiles (Urbina-Cardona et al. 2006; Edgar et al. 2010). These zones are characterized by having a diverse range of plant species and habitat structures, providing various microhabitats and microclimates that are particularly favored by reptiles (Edgar et al. 2010). Pinto et al. (2018) found that a Mediterranean lizard, *Psammodromus algirus*, showed a positive reaction to habitat diversity, with its population growing as habitat complexity increased. Furthermore, to ensure the viability of *E. argus* populations, it is crucial to preserve habitat connectivity and natural dispersal dynamics (Park et al. 2014).

The population size and distribution of *E. argus* may be related to factors shaped by surrounding vegetation, such as food availability, preferences for specific microhabitats, or interspecific interactions. Some preys of *E. argus* are known (grasshoppers, beetles, ants, leafhoppers, moths, bees, and spiders), which belong to Orthoptera, Lepidoptera, Araneae, Dermaptera, and Amphipoda, among others (Jeong and Song 2010; Huang et al. 2016). In our study, Poaceae family plants accounted for the highest proportion, comprising 25 species among 69 total plant species, providing *E. argus* populations protection from predators and allowing light to enter between the plants and help *E. argus* populations to bask properly (Kim et al. 2011; Chang et al. 2021). Although this study did not unveil the intricate connections among vegetation, soil, and food sources, future studies investigating habitat characteristics (vegetation structure and soil) and prey sources should yield additional knowledge to help inform a conservation strategy for *E. argus*.

Conclusions

This study investigated the soil environmental factors and vegetation composition of Doriseom Island, South Korea, where *E. argus* has been found. The island was divided into two zones: the frequently occurring *E. argus* area (F zone) and the rarely occurring *E. argus* area (R zone). The results revealed significant differences in soil hardness and cobble cover between the F and R zones. The R zone had higher soil hardness (1.6 ± 0.2 kg·cm^{-2}) and greater cobble cover (40 ± 5%) compared to the F zone (soil hardness: 0.9 ± 0.1 kg·cm^{-2}; cobble cover: 18 ± 3%). However, plant litter cover did not show significant variation based on *E. argus* occurrence. Distinct differences were observed in vegetation composition between the F and R zones, although *Coreopsis lanceolata* was dominant in both areas. *Carex pumila*, a sand dune sedge, thrived in the F zone where soil hardness was low, while the endemic *Aster danyangensis*, which prefers cobble areas, was predominantly found in the R zone. In conclusion, *E. argus* preferred environments with low soil hardness that were dominated by dune vegetation. Understanding the environmental requirements of endangered species like *E. argus* is crucial for developing effective conservation and restoration strategies. To provide inhabitable environments for the endangered lizard *E. argus* and endemic plant *A. danyangensis* within Doriseom Island, it is crucial to create a diverse soil environment (including sand and cobble). Additionally, it is important to prevent the spread of invasive plants and protect against excessive riverside development.

Acknowledgements

We thank Kyo-Sung Koo for *E. argus* species identification.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Funding

The present research was supported by the research fund of Dankook University in 2021 (R202100726).

Author contributions

Eunhee Cho, fieldwork, plants identification, data analysis and document writing; Deokjoo Son, fieldwork, plants identification, document writing and completed document review.

Author ORCIDs

Eunhee Cho https://orcid.org/0009-0009-8024-3849
Deokjoo Son https://orcid.org/0000-0003-0508-6619

Data availability

All of the data that support the findings of this study are available in the main text

References

Ali W, Javid A, Hussain A, Bukhari SM (2018) Diversity and habitat preferences of amphibians and reptiles in Pakistan: A review. Journal of Asia-Pacific Biodiversity 11(2): 173–187. https://doi.org/10.1016/j.japb.2018.01.009

Amrein D, Rusterholz H-P, Baur B (2005) Disturbance of suburban *Fagus* forests by recreational activities: Effects on soil characteristics, above-ground vegetation and seed bank. Applied Vegetation Science 8: 175–182.

Arifin M, Okamoto T (2023) Floral scent and pollination of the invasive plant *Coreopsis lanceolata* in Japan. Journal of Pollination Ecology 32: 108–127. https://doi.org/10.26786/1920-7603(2023)740

Attum O, Eason P, Cobbs G, Baha El Din SM (2006) Response of a desert lizard community to habitat degradation: Do ideas about habitat specialists/generalists hold? Biological Conservation 133(1): 52–62. https://doi.org/10.1016/j.biocon.2006.05.017

Auliya M, Altherr S, Ariano-Sanchez D, Baard EH, Brown C, Brown R, Cantu J-C, Gentile G, Gildenhuys P, Henningheim E, Hintzmann J, Kanari K, Krvavac M, Lettink M, Lippert J, Luiselli L, Nilson G, Nguyen TQ, Nijman V, Parham JF, Pasachnik SA, Pedrono M, Rauhaus A, Córdova DR, Sanchez M-E, Schepp U, van Schingen M, Schneeweiss N, Segniagbeto GH, Somaweera R, Sy EY, Türkozan O, Vinke S, Vinke T, Vyas R, Williamson S, Ziegler T (2016) Trade in live reptiles, its impact on wild populations, and the role of the European market. Biological Conservation 204: 103–119. https://doi.org/10.1016/j.biocon.2016.05.017

Bakhshandeh S, Norouzi M, Heidari S, Bakhshandeh S (2014) The role of parent material on soil properties in sloping areas under tea plantation in Lahijan, Iran. Carpathian Journal of Earth and Environmental Sciences 9(3): 159–170.

Batianoff GN, Halford DA (2002) *Coreopsis lanceolata* L. (Asteraceae): Another environmental weed for Queensland and Australia. Plant Protection Quarterly 17(4): 168–169.

Burgess RE (1984) The life history strategy of *Carex pumila* Thunb. (Cyperaceae), a rhizomatous perennial pioneer species on the sand plains of the dune system of coastal Manawatu. Dissertations & Theses, Massey University, Palmerston North.

Burns JH (2006) Relatedness and environment affect traits associated with invasive and noninvasive introduced Commelinaceae. Ecological Applications 16(4): 1367–1376. https://doi.org/10.1890/1051-0761(2006)016[1367:RAEATA]2.0.CO;2

Carpio AJ, Castro J, Mingo V, Tortosa FS (2017) Herbaceous cover enhances the squamate reptile community in woody crops. Journal for Nature Conservation 37: 31–38. https://doi.org/10.1016/j.jnc.2017.02.009

Cazzuffi D, Cardile G, Gioffre D (2014) Geosynthetic engineering and vegetation growth in soil reinforcement applications. Transportation Infrastructure Geotechnology 1(3–4): 262–300. https://doi.org/10.1007/s40515-014-0016-1

Chang MH, Song JY, Koo KS (2021) Effect of coastal dune restoration on the population of endangered Mongolian racerunner (*Eremias argus*) in the Republic of Korea. Journal of Coastal Conservation 25(2): 1–29. https://doi.org/10.1007/s11852-021-00820-9

Chang J, Pan Y, Liu W, Xie Y, Hao W, Xu P, Wang Y (2022) Acute temperature adaptation mechanisms in the native reptile species *Eremias argus*. The Science of the Total Environment 818: e151773. https://doi.org/10.1016/j.scitotenv.2021.151773

Chen Z-S, Hsieh C-F, Jiang F-Y, Hsieh T-H, Sun IF (1997) Relations of soil properties to topography and vegetation in a subtropical rain forest in southern Taiwan. Plant Ecology 132(2): 229–241. https://doi.org/10.1023/A:1009762704553

Chen L, Xu P, Diao J, Di S, Li R, Zhou Z (2016) Distribution, metabolism and toxic effects of beta-cypermethrin in lizards (*Eremias argus*) following oral administration. Journal of Hazardous Materials 306: 87–94. https://doi.org/10.1016/j.jhazmat.2015.11.053

Cordier JM, Aguilar R, Lescano JN, Leynaud GC, Bonino A, Miloch D, Loyola R, Nori J (2021) A global assessment of amphibian and reptile responses to land-use changes. Biological Conservation 253: e108863. https://doi.org/10.1016/j.biocon.2020.108863

Do MS, Son S-J, Choi G, Yoo N, Kim D, Koo K-S, Nam H-K (2022) The establishment of ecological conservation for herpetofauna species in hotspot areas of South Korea. Scientific Reports 12(1): e14839. https://doi.org/10.1038/s41598-022-19129-0

Doherty TS, Balouch S, Bell K, Burns TJ, Feldman A, Fist C, Garvey TF, Jessop TS, Meiri S, Driscoll DA (2020) Reptile responses to anthropogenic habitat modification: A global meta-analysis. Global Ecology and Biogeography 29(7): 1265–1279. https://doi.org/10.1111/geb.13091

Doherty TS, Hays GC, Driscoll DA (2021) Human disturbance causes widespread disruption of animal movement. Nature Ecology & Evolution 5(4): 513–519. https://doi.org/10.1038/s41559-020-01380-1

Dueñas M-A, Hemming DJ, Roberts A, Diaz-Soltero H (2021) The threat of invasive species to IUCN-listed critically endangered species: A systematic review. Global Ecology and Conservation 26: e01476. https://doi.org/10.1016/j.gecco.2021.e01476

Edgar P, Foster J, Baker J (2010) Reptile Habitat Management Handbook. Amphibian and Reptile Conservation. Bournemouth.

Garden JG, Mcalpine CA, Possingham HP, Jones DN (2007) Habitat structure is more important than vegetation composition for local-level management of native terrestrial reptile and small mammal species living in urban remnants: A case study from Brisbane, Australia. Austral Ecology 32(6): 669–685. https://doi.org/10.1111/j.1442-9993.2007.01750.x

Gastwirth J, Gel Y, Hui W, Lyubchich V, Miao W, Noguchi K (2020) lawstat: Tools for biostatistics, public policy, and law. R package version 3.4. https://CRAN.R-project.org/package=lawstat

Gibbons JW, Scott DE, Ryan TJ, Buhlmann KA, Tuberville TD, Metts BS, Greene JL, Mills T, Leiden Y, Poppy S, Winne CT (2000) The global decline of reptiles, déjà vu amphibians: Reptile species are declining on a global scale. six significant threats to reptile populations are habitat loss and degradation, introduced invasive species, environmental pollution, disease, unsustainable use, and global climate change. Bioscience 50(8): 653–666. https://doi.org/10.1641/0006-3568(2000)050[0653:TGDORD]2.0.CO;2

Huang D, Wang K, Wu WL (2007) Dynamics of soil physical and chemical properties and vegetation succession characteristics during grassland desertification under sheep grazing in an agro-pastoral transition zone in Northern China. Journal of Arid Environments 70(1): 120–136. https://doi.org/10.1016/j.jaridenv.2006.12.009

Huang X, Wu H, Tu X, Zhang Z, Su H, Shi Y, Wang G, Cao G, Nong X, Zhang Z (2016) Diets structure of a common lizard *Eremias argus* and their effects on grasshoppers: Implications for a potential biological agent. Journal of Asia-Pacific Entomology 19(1): 133–138. https://doi.org/10.1016/j.aspen.2015.12.013

IUCN (2023) The IUCN Red List of Threatened Species. Version 2022-2. https://www.iucnredlist.org [Accessed June 10, 2023]

Jellinek S, Driscoll DA, Kirkpatrick JB (2004) Environmental and vegetation variables have a greater influence than habitat fragmentation in structuring lizard communities in remnant urban bushland. Austral Ecology 29(3): 294–304. https://doi.org/10.1111/j.1442-9993.2004.01366.x

Jeong J-C, Song JY (2010) Diet composition of the Korean leopard lizard, *Eremias argus* (Reptilia:Lacertidae) in Taeanhaean National Park. Journal of National Park Research 1(1): 9–12. [In Korean]

Kagaya M, Tani T, Kachi N (2008) Effect of gravel conditions on seedling emergence of the endangered monocarpic perennial *Aster kantoensis* (Compositae) on a floodplain. Plant Species Biology 23(1): 47–50. https://doi.org/10.1111/j.1442-1984.2008.00207.x

KIE [National Institute of Ecology] (2018) Investigating Ecological Risk of Alien Species (V).

Kim J-k, Kim I-H, Ra N-Y, Park D (2011) Characteristics of *Eremias argus* habitat in coastal sand dunes and mountain areas. The Korean Journal of Hepatology 3: 11–18. https://doi.org/10.3724/SP.J.1245.2012.00133

Kim B-N, Kim J-K, Park D (2012a) Mating behavior of the Mongolian racerunner (*Eremias argus*; Lacertidae, Reptilia). Animal Cells and Systems 16(4): 337–342. https://doi.org/10.1080/19768354.2012.657242

Kim I-H, Ra N-Y, Park D (2012b) Habitat use, home range, and hibernaculum of the Mongolian racerunner, *Eremias argus* (Lacertidae, Reptilia) in a coastal sand dune in South Korea. Asian Herpetological Research 3(2): 133–140. https://doi.org/10.3724/SP.J.1245.2012.00133

Kim JY, Jo HJ, Chang KS, Son DC, Chung GY (2022) Aster danyangensis, a replacement name for *Aster altaicus* var. *uchiyamae* (Asteraceae). Korean Journal of Plant Taxonomy 52(1): 77–79. https://doi.org/10.11110/kjpt.2022.52.1.77

KMA [Korea Meteorological Administration] (2023) Korea Meteorological Administration. https://www.weather.go.kr/w/obs-climate/land/past-obs/obs-by-day.do [Accessed June 5, 2023]

Korea National Arboretum (2022) English Names for Korean Native Plants (revised edn.). Korea National Arboretum, Pocheon, 723 pp.

Kortz AR, Magurran AE (2019) Increases in local richness (α-diversity) following invasion are offset by biotic homogenization in a biodiversity hotspot. Biology Letters 15(5): e20190133. https://doi.org/10.1098/rsbl.2019.0133

Lee TB (2003) Coloured Flora of Korea. Hyang Mun Sa. Seoul, Korea. [in Korean]

Lee BE, Kim J, Kim N-I, Kim JG (2017) Evaluation on replacement habitat of two endangered species, *Aster altaicus* var. *uchiyamae* and *Polygonatum stenophyllum* using habitat suitability index. Journal of Wetlands Research 19(4): 433–442.

Lee J-Y, Cheong J-H, Kim H-S (2020) A study monitoring the changes in Taean sindu coastal sand dune vegetation. The Journal of Korean Island 32(3): 187–202. https://doi.org/10.26840/JKI.32.3.187 [In Korean]

Macias D, Shin Y, Borzée A (2021) An update on the conservation status and ecology of Korean terrestrial squamates. Journal for Nature Conservation 60: e125971. https://doi.org/10.1016/j.jnc.2021.125971

Májeková M, Paal T, Plowman NS, Bryndová M, Kasari L, Norberg A, Weiss M, Bishop TR, Luke SH, Sam K, Le Bagousse-Pinguet Y, Lepš J, Götzenberger L, de Bello F (2016) Evaluating functional diversity: Missing trait data and the importance of species abundance structure and data transformation. PLOS ONE 11(2): e0149270. https://doi.org/10.1371/journal.pone.0149270

Martin LJ, Murray BR (2011) A predictive framework and review of the ecological impacts of exotic plant invasions on reptiles and amphibians. Biological Reviews of the Cambridge Philosophical Society 86(2): 407–419. https://doi.org/10.1111/j.1469-185X.2010.00152.x

Mathakutha R, Steyn C, le Roux PC, Blom IJ, Chown SL, Daru BH, Ripley BS, Louw A, Greve M (2019) Invasive species differ in key functional traits from native and non-invasive alien plant species. Journal of Vegetation Science 30(5): 994–1006. https://doi.org/10.1111/jvs.12772

Menke SB (2003) Lizard community structure across a grassland – creosote bush ecotone in the Chihuahuan Desert. Canadian Journal of Zoology 81(11): 1829–1838. https://doi.org/10.1139/z03-184

Mizsei E, Fejes Z, Malatinszky Á, Lengyel S, Vadász C (2020) Reptile responses to vegetation structure in a grassland restored for an endangered snake. Community Ecology 21(2): 203–212. https://doi.org/10.1007/s42974-020-00019-2

National Geographic Information Institute (2021) National Geographic Information Institute. https://www.ngii.go.kr/kor/main.do [Accessed January 6, 2024]

Ngo-Cong D, Antille DLT, van Genuchten M, Nguyen HQ, Tekeste MZ, Baillie CP, Godwin RJ (2021) A modeling framework to quantify the effects of compaction on soil water retention and infiltration. Soil Science Society of America Journal 85(6): 1931–1945. https://doi.org/10.1002/saj2.20328

Oh S-H, Kim H-J (2008) The plant resources of the sand dune on southern coast and Jeju Island, Korea. Korean Journal of Plant Resources 21(5): 374–387.

Oksanen J, Simpson G, Blanchet F, Kindt R, Legendre P, Minchin P, O'Hara R, Solymos P, Stevens M, Szoecs E, Wagner H, Barbour M, Bedward M, Bolker B, Borcard D, Carvalho G, Chirico M, De Caceres M, Durand S, Evangelista H, FitzJohn R, Friendly M, Furneaux B, Hannigan G, Hill M, Lahti L, McGlinn D, Ouellette M, Ribeiro Cunha E, Smith T, Stier A, Ter Braak C, Weedon J (2022) vegan: Community Ecology Package. R package version 2.6-4. https://CRAN.R-project.org/package=vegan

Orlova V, Terbish K, Zhao W, Guo X (2019) *Eremias argus*. The IUCN Red List of Threatened Species 2019: e.T47755847A47755852. https://doi.org/10.2305/IUCN.UK.2019-3.RLTS.T47755847A47755852.en [Accessed June 19, 2023]

Pacanoski Z (2017) Current situation with invasive *Erigeron annuus* (L.) Pers. (daisy fleabane) in the Republic of Macedonia. Bulletin OEPP. EPPO Bulletin. European and Mediterranean Plant Protection Organisation 47(1): 118–124. https://doi.org/10.1111/epp.12368

Park S (2009) New illustrations and photographs of naturalized plants of Korea. Ilchokak, Seoul, Korea. [In Korean]

Park H-C, Suk HY, Jeong E-J, Park D-S, Lee H, Min M-S (2014) Population genetic structure of endangered Mongolian racerunner (*Eremias argus*) from the Korean Peninsula. Molecular Biology Reports 41(11): 7339–7347. https://doi.org/10.1007/s11033-014-3623-6

Pinto T, Moreira B, Freitas H, Santos X (2018) The role of fire history, land-use, and vegetation structure on the response of Mediterranean lizards to fire. Forest Ecology and Management 419–420: 139–145. https://doi.org/10.1016/j.foreco.2018.03.029

R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/

Reynolds HL, Packer A, Bever JD, Clay K (2003) Grassroots ecology: Plant–microbe–soil interactions as drivers of plant community structure and dynamics. Ecology 84(9): 2281–2291. https://doi.org/10.1890/02-0298

Sato CF, Wood JT, Schroder M, Green K, Osborne WS, Michael DR, Lindenmayer DB (2014) An experiment to test key hypotheses of the drivers of reptile distribution in subalpine ski resorts. Journal of Applied Ecology 51(1): 13–22. https://doi.org/10.1111/1365-2664.12168

Scott DM, Brown D, Mahood S, Denton B, Silburn A, Rakotondraparany F (2006) The impacts of forest clearance on lizard, small mammal and bird communities in the arid spiny forest, southern Madagascar. Biological Conservation 127(1): 72–87. https://doi.org/10.1016/j.biocon.2005.07.014

Singh J, Salaria A, Kaul A (2015) Impact of soil compaction on soil physical properties and root growth: A review. International Journal of Food. Agriculture and Veterinary Sciences 5(1): 23–32.

Song J-Y, Chang M-H, Koo K-S (2013) Estimating the size of a Mongolian racerunner *Eremias argus* (Squamata: Lacertidae) population at Baramarae beach, Taeanhaean National Park. The Korean Journal of Hepatology 5: 9–13.

Souter NJ, Bull CM, Lethbridge MR, Hutchinson MN (2007) Habitat requirements of the endangered pygmy bluetongue lizard, Tiliqua adelaidensis. Biological Conservation 135(1): 33–45. https://doi.org/10.1016/j.biocon.2006.09.014

Stokes A, Douglas GB, Fourcaud T, Giadrossich F, Gillies C, Hubble T, Kim JH, Loades KW, Mao Z, McIvor IR, Mickovski SB, Mitchell S, Osman N, Phillips C, Poesen J, Polster D, Preti F, Raymond P, Rey F, Schwarz M, Walker LR (2014) Ecological mitigation of hillslope instability: Ten key issues facing researchers and practitioners. Plant and Soil 377(1): 1–23. https://doi.org/10.1007/s11104-014-2044-6

Sun B-J, Li S-R, Xu X-F, Zhao W-G, Luo L-G, Ji X, Du W-G (2013) Different mechanisms lead to convergence of reproductive strategies in two lacertid lizards (*Takydromus wolteri* and *Eremias argus*). Oecologia 172(3): 645–652. https://doi.org/10.1007/s00442-012-2524-4

Unger PW, Kaspar TC (1994) Soil compaction and root growth: A review. Agronomy Journal 86(5): 759–766. https://doi.org/10.2134/agronj1994.00021962008600050004x

Urbina-Cardona JN, Olivares-Pérez M, Reynoso VH (2006) Herpetofauna diversity and microenvironment correlates across a pasture–edge–interior ecotone in tropical rainforest fragments in the Los Tuxtlas Biosphere Reserve of Veracruz, Mexico. Biological Conservation 132(1): 61–75. https://doi.org/10.1016/j.biocon.2006.03.014

Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, Pergl J, Schaffner U, Sun Y, Pyšek P (2011) Ecological impacts of invasive alien plants: A meta-analysis of their effects on species, communities and ecosystems. Ecology Letters 14(7): 702–708. https://doi.org/10.1111/j.1461-0248.2011.01628.x

Wang Z, Zhu W, Xu Y, Yu S, Zhang L, Zhou Z, Diao J (2021) Effects of simazine and food deprivation chronic stress on energy allocation among the costly physiological processes of male lizards (*Eremias argus*). Environmental Pollution 269: e116139. https://doi.org/10.1016/j.envpol.2020.116139

Watson GW, Kelsey P (2006) The impact of soil compaction on soil aeration and fine root density of *Quercus palustris*. Urban Forestry & Urban Greening 4(2): 69–74. https://doi.org/10.1016/j.ufug.2005.08.001

Wickham H (2016) ggplot2: Elegant graphics for data analysis. Springer-Verlag New York. [ISBN 978-3-319-24277-4] https://ggplot2.tidyverse.org

Zaady E, Bouskila A (2002) Lizard burrows association with successional stages of biological soil crusts in an arid sandy region. Journal of Arid Environments 50(2): 235–246. https://doi.org/10.1006/jare.2001.0953

Zeng J, Xiao Y, Sun M, Zhou B (2014) Effect of clonal growth on mating system of invasive plant *Coreopsis lanceolata*. Bulletin of Botanical Research 34(5): 650–654.

Zeng Z-G, Bi J-H, Li S-R, Wang Y, Robbins TR, Chen S-Y, Du W-G (2016) Habitat alteration influences a desert steppe lizard community: Implications of species-specific preferences and performance. Herpetological Monograph 30(1): 34–48. https://doi.org/10.1655/HERPMONOGRAPHS-D-14-00008.1

Zhao Q, Liu H-X, Luo L-G, Ji X (2011) Comparative population genetics and phylogeography of two lacertid lizards (*Eremias argus* and *E. brenchleyi*) from China. Molecular Phylogenetics and Evolution 58(3): 478–491. https://doi.org/10.1016/j.ympev.2010.12.017

Zimmerman DW, Zumbo BD (1993) Rank transformations and the power of the Student *t* test and Welch *t' test* for non-normal populations with unequal variances. Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale 47(3): e523. https://doi.org/10.1037/h0078850

Appendix 1

Table A1. Plant species code and scientific name.

Species code	Scientific name	Family	Common name	Zone
A.ar	*Ambrosia artemisiifolia* L.	Asteraceae	Common ragweed (돼지풀)	F, R
A.ca	*Artemisia capillaris* Thunb.	Asteraceae	Capillary wormwood (사철쑥)	F, R
A.da	*Aster danyangensis* J.Y.Kim & G.Y.Chung	Asteraceae	Danyang aster (단양쑥부쟁이)	R
A.fr	*Amorpha fruticosa* L.	Fabaceae	False indigo-bush (족제비싸리)	R
A.in	*Artemisia indica* Willd.	Asteraceae	Korean wormwood (쑥)	F, R
A.se	*Arenaria serpyllifolia* L.	Caryophyllaceae	Thyme-leaf sandwort (벼룩이자리)	F, R
B.co	*Bromus commutatus* Schrad.	Poaceae	Hairy chess (털큰참새귀리)	F
B.ja	*Bromus japonicus* Thunb.	Poaceae	Common brome (참새귀리)	F, R
B.st	*Bromus sterilis* L.	Poaceae	Barren brome (까락빕새귀리)	F
C.bi	*Cosmos bipinnatus* Cav.	Asteraceae	Garden cosmos (코스모스)	F
C.br	*Carex breviculmis* R.Br.	Cyperaceae	Short-stem sedge (청사초)	F, R
C.gl	*Carex glabrescens* (Kük.) Ohwi	Cyperaceae	Glabrate sedge (곱슬사초)	F, R
C.la	*Coreopsis lanceolata* L.	Asteraceae	Lanceleaf coreopsis (큰금계국)	F, R
C.pu	*Carex pumila* Thunb.	Cyperaceae	Dwarf sand sedge (좀보리사초)	F
Cyp1	N/A (Cyperaceae species 1)	Cyperaceae	Cyperaceae species 1 (사초과 1)	F
Cyp2	N/A (Cyperaceae species 2)	Cyperaceae	Cyperaceae species 2 (사초과 2)	F
Cyp3	N/A (Cyperaceae species 3)	Cyperaceae	Cyperaceae species 3 (사초과 3)	R
D.ch	*Dianthus chinensis* L.	Caryophyllaceae	Rainbow pink (패랭이꽃)	F, R

Species code	Scientific name	Family	Common name	Zone
D.in	*Duchesnea indica* (Andrews) Teschem.	Rosaceae	Wrinkled mock strawberry (뱀딸기)	R
D.ne	*Draba nemorosa* L.	Brassicaceae	Woodland whitlow-grass (꽃다지)	F
E.an	*Erigeron annuus* (L.) Pers.	Asteraceae	Annual fleabane (개망초)	F, R
E.ar	*Equisetum arvense* L.	Equisetaceae	Field horsetail (쇠뜨기)	F, R
E.hy	*Equisetum hyemale* L.	Equisetaceae	Scouringrush horsetail (속새)	F, R
E.ra	*Equisetum ramosissimum* Desf.	Equisetaceae	Branched horsetail (개속새)	F, R
E.ts	*Elymus tsukushiensis* Honda var. *transiens* (Hack.) K.Osada	Poaceae	Wheatgrass (개밀)	F
F.ar	*Festuca arundinacea* Schreb.	Poaceae	Tall fescue (큰김의털)	F, R
F.du	*Fallopia dumetorum* (L.) Holub	Polygonaceae	Copse buckwheat (닭의덩굴)	F
G.ve	*Galium verum* L. subsp. *asiaticum* (Nakai) T.Yamaz.	Rubiaceae	Asian yellow spring bedstraw (솔나물)	F
H.ly	*Hemisteptia lyrata* (Bunge) Fisch. & C.A.Mey	Asteraceae	Lyre-shape hemistepta (지칭개)	F
H.sc	*Humulus scandens* (Lour.) Merr.	Cannabaceae	Wild hop (환삼덩굴)	F, R
I.cy	*Imperata cylindrica* (L.) Raeusch.	Poaceae	Blady grass (띠)	F
L.ch	*Leymus chinensis* (Trin.) Tzvelev	Poaceae	False wheatgrass (개밀아재비)	R
L.cu	*Lespedeza cuneata* (Dum.Cours.) G.Don	Fabaceae	Sericea lespedeza (비수리)	F, R
L.su	*Leucanthemum × superbum* (Bergmans ex J.W.Ingram) D.H.Kent	Asteraceae	Shasta daisy (샤스타데이지)	R
L.vi	*Lepidium virginicum* L.	Brassicaceae	Virginia peppergrass (콩다닥냉이)	F, R
Lil1	N/A (Liliaceae species 1)	Liliaceae	Liliaceae species 1 (백합과 1)	F, R
M.ja	*Metaplexis japonica* (Thunb.) Makino	Apocynaceae	Rough potato (박주가리)	R
M.sa	*Miscanthus sacchariflorus* (Maxim.) Benth. & Hool.f. ex Franch.	Poaceae	Amur silvergrass (물억새)	F
M.sc	*Melica scabrosa* Trin.	Poaceae	Rough melic (참쌀새)	R
M.si	*Miscanthus sinensis* Andersson var. *purpurascens* (Andersson) Matsum.	Poaceae	Purple maiden silvergrass (억새)	F, R
O.bi	*Oenothera biennis* L.	Onagraceae	Evening primrose (달맞이꽃)	F, R
P.ar	*Phalaris arundinacea* L.	Poaceae	Reed canary grass (갈풀)	R
P.ar2	*Plantago aristata* Michx.	Plantaginaceae	Bracted plantain (긴포꽃질경이)	R
P.au	*Phragmites australis* (Cav.) Trin. ex Steud.	Poaceae	Common reed (갈대)	R
P.ch	*Potentilla chinensis* Ser.	Rosaceae	East Asian cinquefoil (딱지꽃)	F, R
P.de	*Populus nigra* L.	Salicaceae	Black poplar (양버들)	R
P.hy	*Persicaria hydropiper* (L.) Delarbre	Polygonaceae	Water pepper (여뀌)	F
P.pe	*Persicaria perfoliata* (L.) H.Gross	Polygonaceae	Asian tearthumb (며느리배꼽)	R
P.pr	*Poa pratensis* L.	Poaceae	Kentucky bluegrass (왕포아풀)	F, R
P.sp	*Poa sphondylodes* Trin.	Poaceae	Hard bluegrass (포아풀)	F
Poa1	N/A (Poaceae species 1)	Poaceae	Poaceae species 1 (벼과 1)	F, R
Poa2	N/A (Poaceae species 2)	Poaceae	Poaceae species 2 (벼과 2)	F
Poa3	N/A (Poaceae species 3)	Poaceae	Poaceae species 3 (벼과 3)	R
Poa4	N/A (Poaceae species 4)	Poaceae	Poaceae species 4 (벼과 4)	F
Poa5	N/A (Poaceae species 5)	Poaceae	Poaceae species 5 (벼과 5)	F, R
Poa6	N/A (Poaceae species 6)	Poaceae	Poaceae species 6 (벼과 6)	R
Poa7	N/A (Poaceae species 7)	Poaceae	Poaceae species 7 (벼과 7)	R
Poa8	N/A (Poaceae species 8)	Poaceae	Poaceae species 8 (벼과 8)	F
R.cr	*Rumex crispus* L.	Polygonaceae	Curly dock (소리쟁이)	R
R.pa	*Rubus parvifolius* L.	Rosaceae	Trailing raspberry (멍석딸기)	R
R.ps	*Robinia pseudoacacia* L.	Fabaceae	Black locust (아까시나무)	F, R
S.ar	*Silene armeria* L.	Caryophyllaceae	Sweet william catchfly (끈끈이대나물)	F
S.sa	*Sedum sarmentosum* Bunge	Crassulaceae	Ster sedum (돌나물)	R
S.vi	*Setaria viridis* (L.) P.Beauv.	Poaceae	Bristlegrass (강아지풀)	F
T.gl	*Turritis glabra* L.	Brassicaceae	Tower rockcress (장대나물)	F, R
T.tr	*Themeda triandra* Forssk.	Poaceae	Brush grass (솔새)	F, R
V.am	*Vicia amurensis* Oett.	Fabaceae	Amur vetch (벌완두)	F
V.ma	*Viola mandshurica* W.Becker	Violaceae	Manchurian violet (제비꽃)	F, R
Z.ja	*Zoysia japonica* Steud.	Poaceae	Korean lawngrass (잔디)	F, R