Biological, Social, and Institutional Asynchrony in Invasive Species Management: A Multi-proxy Analysis of Hypochaeris radicata on the Jeju Island

Sangsun Lee
National Institute of Ecology
Hyerin Yu
yuhrin17@nie.re.kr
National Institute of Ecology

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Abstract

Strategic management of invasive alien species is often hindered by a "management paradox": delayed intervention only after rapid biological expansion. Accordingly, here, we propose a more coordinated and proactive national biosecurity framework. We evaluated temporal synchrony among biological expansion, social perception, and institutional response using the 40-year invasion history of *Hypochaeris radicata* on the Jeju Island. We employed a multi-proxy approach that integrated historical herbarium specimens, coordinate-based occurrence records corrected using the effective range radius with count-based effort correction, and a semantic network analysis of news media discourse from 1999 to 2025. We identified precise biological inflection points via a segmented regression analysis and compared them with the timing of "social visibility thresholds." Our analysis revealed a profound temporal asynchrony within the socio-ecological system. Social recognition in news media emerged as early as 1999, capturing ecological shifts nearly 7 years before the primary biological acceleration point was identified in June 2006. Despite early social awareness and the impending biological surge, formal legal designation as an Ecosystem Disturbing Species was delayed until 2009. By the time policy action was mandated, *H. radicata* had bypassed the window for cost-effective eradication and entered a saturation phase (2018), achieving regional habitat stabilization. The 20-year administrative lag exemplifies a systemic “knowing-doing gap” driven by institutional fragmentation and cognitive normalization. To prevent future "invasion debts," national biosecurity frameworks must transition to a dynamic phase-specific early detection and rapid response system that utilizes social and media trends as proactive triggers for legislative action.

1. Introduction

Biological invasions by alien plants drive global environmental change. These invasions often cause irreversible biodiversity loss and compromise essential ecosystem services (Ahmed et al. 2022; IPBES 2023). Rapid globalization and international trade have substantially amplified both the frequency and volume of unintentional and intentional plant introductions, with invasive alien species (IAS) spreading across virtually all terrestrial biomes at unprecedented rates (Cuthbert et al. 2022; IPBES 2023). The cumulative ecological and socio-economic costs of these invasions are staggering—amounting to trillions of dollars in annual global economic damage (Diagne et al. 2021)—and are further compounded by biodiversity loss and the degradation of ecosystem integrity that frequently prove irreversible on human timescales. Despite these escalating costs, conventional strategies for IAS management have predominantly focused on the static spatial distribution of already-established populations—an approach that lacks the predictive capacity required for proactive, cost-effective intervention (Ahmed et al. 2022). A fundamental paradigm shift from reactive space-oriented monitoring to a robust mechanistic understanding of temporal invasion dynamics is therefore imperative (Crooks 2005; Aikio et al. 2010).

As a conceptual framework for understanding such temporal dynamics, the spatiotemporal progression of biological invasions is fundamentally conceptualized as a non-linear triphasic trajectory that comprises an initial establishment period (lag phase) of slow and cryptic population growth, a

subsequent acceleration phase involving rapid range expansion, and a terminal saturation stage (Kowarik 1995; Ward et al. 2020; Ni 2023). Strategic management efficacy is strictly stage-dependent: proactive eradication is ecologically and economically viable only during the low-density lag phase, whereas containment and impact mitigation become inevitable—yet markedly less efficient—once a population surpasses the biological inflection point that marks the transition from lagging increase to explosive acceleration (Mehta et al. 2007; Ahmed et al. 2022). Precise identification of this inflection point, therefore, functions as a core prerequisite for successful strategic management (Crooks 2005; Aikio et al. 2010; Larkin 2012).

Despite these well-established theoretical principles, invasive plant management in practice is systematically hindered by a "management paradox," where the optimal window for cost-effective intervention coincides precisely with the period when populations are the smallest in extent, most cryptic in detection, and least likely to be perceived as a significant ecological threat (Crooks 2005; Ng and Driscoll 2015). This detection lag translates directly into a parallel administrative challenge: the legal recognition of a species as invasive frequently fails to synchronize with the prolonged biological reality of lag dynamics, resulting in a critical breakdown of "policy timeliness"—the alignment of regulatory intervention with early-stage invasion dynamics (Tasker 2011; Ahmed et al. 2022). Failure to execute administrative action before the acceleration phase results in an exponential escalation of the "cost of inaction," rendering late-stage reactive control both ecologically futile and economically prohibitive (Duncan 2021; Cuthbert et al. 2022). Therefore, evaluating the temporal asynchrony between biological invasion dynamics and policy execution is academically critical and essential for optimizing the allocation of finite conservation resources and preventing further irreversible ecological degradation and the concomitant fiscal burdens.

This fiscal inefficiency is evidenced by the disproportionate allocation of economic resources toward post-establishment control rather than prevention. Global evidence indicates that the costs of reactive management are at least 25 times greater than those of proactive biosecurity, representing a substantial "cost of inaction" (Cuthbert et al. 2022; Ahmed et al. 2022). The IPBES (2023) assessment further underscores this disparity, reporting that global annual costs now exceed US$423 billion, with over 90% of these expenditures resulting from environmental damage rather than management investment. This fiscal imbalance is not merely a consequence of scientific uncertainty but stems from a persistent "knowing-doing gap," wherein scientific insights into invasion risks are not translated into management interventions in a timely manner (Esler et al. 2010). Such delays are often exacerbated by institutional lag and the inherently reactive nature of policy frameworks, which typically mobilize resources only after ecological threats become socially visible and populations reach an unmanageable acceleration phase (Simberloff et al. 2005; Khuroo et al. 2011). Historically, these administrative bottlenecks have resulted in significant eradication failures; for instance, the delayed regulatory response to invasive plants such as *Lantana camara* allowed them to surpass critical biological inflection points, rendering subsequent control efforts both costly and ecologically ineffective (Khuroo et al. 2011). While these global trends are evident, localized empirical studies that quantitatively bridge the gap between biological expansion and policy timing remain scarce.

The need for such an empirical evaluation of policy timeliness is particularly exemplified by *Hypochaeris radicata* L. (Asteraceae). This perennial herb serves as an instructive model for the rapid transition from initial establishment to invasive acceleration. This species possesses extraordinary invasive potential (Lee et al. 2023), underpinned by its high phenotypic plasticity and superior reproductive output across diverse environmental gradients (Mitchell and Bakker 2014; Lee et al. 2024). A primary driver of its rapid range expansion is its specialized mechanism of anemochory: the minute achenes, equipped with a plumose pappus, exhibit characteristically low terminal velocity, which facilitates long-distance dispersal (LDD) and enables the species to effectively bypass initial colonization barriers as evidenced by both direct LDD measurements (Soons et al. 2004) and population-genetic evidence of high gene flow across fragmented landscapes (Mix et al. 2006). These biological attributes are known to truncate cryptic lag phases, frequently resulting in an abrupt and aggressive shift toward the acceleration phase once environmental thresholds are exceeded (Lee et al. 2024). In South Korea, *H. radicata* was first officially recorded in 1992 and was subsequently designated as an Ecosystem Disturbing Species (EDS) in 2009 to mitigate its escalating ecological impacts (Ministry of Environment Ordinance No. 332; Lee et al. 2023). However, despite this regulatory action, the temporal alignment between the biological onset of explosive spread and the timing of legislative intervention remains unquantified. Assessing whether the 2009 designation occurred proactively relative to the species' biological inflection point is therefore essential for evaluating the empirical efficacy of national biosecurity frameworks.

The necessity for such an empirical evaluation is the most pronounced on the Jeju Island—a UNESCO Biosphere Reserve and one of South Korea's principal biodiversity hotspots (Ryu et al. 2017; Son et al. 2023). Owing to its geographic isolation and finite land area, the island provides an ideal closed-system model for analyzing invasion saturation dynamics and the temporal structure of lag phases in invasive plants. Following the 2009 EDS designation of *H. radicata*, local municipal governments have implemented extensive eradication programs; however, the effectiveness of these reactive measures remains questionable, as such efforts frequently lack species-specific protocols and are often executed as non-systematic, one-time public events rather than sustained, science-based control programs (Kim and Koo 2021). Crucially, such institutional responses are often not a direct consequence of biological thresholds being crossed, but are instead triggered by the social visibility of the species and the ensuing public pressure.

To address these gaps, we integrated biological records with news media coverage, and propose a reliable proxy for social and institutional awareness. Recognizing that institutional action is often driven by social perception rather than raw biological data, news media coverage was utilized as a reliable proxy for social and institutional awareness. We hypothesized that: (1) social recognition, captured through media discourse, exhibits temporal synchronization with the distinct biological expansion phases of *H. radicata*; (2) a significant institutional lag exists, wherein the 2009 legal designation followed both the onset of social visibility and the biological acceleration point, resulting in systemic asynchrony within the socio-ecological response framework. Therefore, the primary objectives of this study were to: (i) delineate the biological invasion trajectory and identify invasion phases through lag phase analysis; (ii) analyze the temporal evolution of public awareness through text mining of news

articles across these defined phases; and (iii) evaluate the degree of alignment among biological reality, social visibility, and policy timeliness to propose a more synchronized, proactive national biosecurity framework. The proposed framework shows that convergent signals across evidence streams are adequate to describe the basic temporal structure of the invasion and the associated institutional response, even in the case of limited historical datasets.

2. Materials and Methods

2.1. Study Area

The study was conducted on the Jeju Island, located at the southern tip of the Korean Peninsula (33°11'–33°33'N, 126°10'–126°59'E). With an area of approximately 1,846 km², the Jeju Island is the largest island in the Republic of Korea (Korean Statistical Information Service 2024). Centered on Mt. Halla (1,947 m a.s.l.), it exhibits a sharp altitudinal gradient from coast to alpine zone, volcanic ash soils, and a temperate oceanic climate. These geographical and climatic characteristics have led to its designation as a UNESCO Biosphere Reserve (2002), a World Natural Heritage Site (2007), and a Global Geopark (2010), positioning it as an internationally recognized biodiversity hotspot (Ryu et al. 2017; Son et al. 2023). However, owing to its geographical isolation and compounding anthropogenic disturbances from tourism, agriculture, livestock, and road development, it is highly vulnerable to alien plant invasions (Ryu et al. 2017). As established alien species on insular ecosystems tend to spread rapidly under continuous re-introduction pressure, the Jeju Island has been widely employed as an ideal closed-system model in invasion ecology (Son et al. 2023).

2.2. Study Species: Hypochaeris radicata

The target species of this study, *Hypochaeris radicata* L. (Asteraceae), is a perennial herb native to the Mediterranean region, with its presumed center of origin in Morocco (Ortiz et al. 2008).

Each individual plant produces 2,300 seeds per year (Turkington and Aarssen 1983), and the seeds are capable of both photoblastic and scotoblastic germination (Ha 2006). The hairy achenes are primarily wind-dispersed: owing to their low terminal velocity conferred by the plumose pappus, they can be carried through LDD, moving at approximately 32.4 cm/s, and can be ectozoochorously dispersed via the fur and limbs of animals (Ridley 1930; Soons et al. 2004). *H. radicata* also exhibits broad environmental plasticity and pronounced tolerance to cold and trampling, enabling it to inhabit areas from the coast up to elevations of 1,700 m (Gleason and Cronquist 1991; Ha 2006).

In Korea, *H. radicata* is presumed to have been introduced in the early 1980s via contaminated pasture-improvement seeds imported from the United States, the Netherlands, and Australia, and to have first been established on the Jeju Island (An 2001). Following the first official voucher specimen in 1992, the species progressively expanded across the Jeju Island (Kim et al. 2020), extending its range onto the Korean mainland (Lee et al. 2023). Underpinned by high phenotypic plasticity and reproductive output, it

has been regarded as a model invasive species exemplifying a rapid transition from initial establishment to explosive range expansion (Mitchell and Bakker 2014; Lee et al. 2024).

2.3. Data Sources

We integrated three independent data streams to reconstruct the multi-decadal invasion trajectory of *H. radicata* on the Jeju Island and evaluate its temporal alignment with social and institutional responses: (i) historical herbarium specimens, (ii) georeferenced occurrence records from systematic vegetation surveys, and (iii) news media articles. The acquisition and characteristics of each data stream are described below.

2.3.1. Herbarium Specimen Records

To reconstruct the long-term temporal presence of *H. radicata* on the Jeju Island, herbarium specimen records were retrieved from the Korea Biodiversity Information System (KNA; https://www.nature.go.kr). Two parameters were extracted from the database for each year of record: (1) the annual number of herbarium specimens identified as *H. radicata*; (2) the annual total number of vascular plant specimens collected on the Jeju Island, which served as the denominator for sampling-effort correction (see Section 2.5.1). As botanical surveys on the Jeju Island have been administered by various regional and national institutions, the consolidated dataset integrates records from multiple herbaria, including but not limited to the Jeju National University, the Korea National Arboretum (KNA), Ewha Womans University, and Chonbuk National University. This multi-institutional consolidation provides a comprehensive representation of the historical botanical collection effort within the study area. The final dataset spans the period from 1981 to 2014, encompassing 34 consecutive annual records (Table S1).

2.3.2. Coordinate Occurrence Records

Georeferenced occurrence records were obtained from EcoBank (National Institute of Ecology 2025), the national biodiversity data repository operated by the National Institute of Ecology, Republic of Korea. To ensure data quality and traceability, only datasets with formally issued Digital Object Identifiers (DOIs) were included. The compiled dataset covered 8 survey years between 2003 and 2022 (2003, 2011, 2013, 2015, 2017, 2020, 2021, 2022), providing both the spatial coordinates of *H. radicata* occurrences and the corresponding total survey coordinates within Jeju Special Self-Governing Province (Figure S2). The list of DOI-registered datasets used in this study is provided in Table S2.

2.3.3. News Media Records

To characterize the temporal evolution of social perception and institutional response, news articles published between December 1999 and December 2025 were retrieved from four major South Korean search engines: Google, Daum, Naver, and Nate. The search was conducted using the Boolean query: ("Jeju" OR "Jeju Island") AND ("Seoyangeumhoncho [Korean scientific name]" OR "Gaemindeulle [Korean common name for *H. radicata*]"). The initial corpus underwent a multi-stage filtering process to ensure thematic relevance. Articles were excluded if they met any of the following criteria: (i) internal duplicates;

(ii) primary focus on regions outside the Jeju Island; or (iii) generic biological descriptions lacking an environmental management context. Conversely, priority was given to articles addressing ecological risk, EDS designation, or specific eradication interventions. This process yielded a final corpus of 71 articles, which were subsequently analyzed to identify chronological shifts in public discourse and institutional trajectories.

2.4. Spatial Framework

2.4.1. Grid Generation

To establish a consistent spatial unit for occupancy quantification, the Jeju Island was divided into 50 × 50 m square grid cells (approximately 2,500 m² per cell). This grid resolution was chosen based on the resolution standards employed in previous spatial spread studies (Ward et al. 2020) and the statistical sufficiency required relative to the island's area. Each grid cell was assigned a unique grid identifier, which served as the primary spatial unit for joining occurrence records and environmental variables.

2.4.2. Identification of Suitable Habitat

Grid cells corresponding to non-suitable habitats were systematically excluded to ensure that subsequent occupancy and expansion metrics reflect biologically meaningful spread rather than spurious detections in non-habitable areas. Two filtering criteria were sequentially applied.

First, because *H. radicata* tends to dominate open, bare, and sunlit habitats while its establishment is considerably restricted under the shaded interior of forests (Ha 2006), the sub-classification land cover map (1:5,000) provided by the Ministry of Environment (2025) was used to assign each grid cell one of three land-cover codes: Level-1 (broad), Level-2 (mid), and Level-3 (detailed). Grids corresponding to Level-1 categories with extremely low invasion potential—including dense forest interior, water bodies, and exposed rocky surfaces—were excluded from the analysis.

Second, given that the highest recorded occurrence elevation of *H. radicata* on the Jeju Island is 1,700 m a.s.l. (Ha 2006), the 1" (approximately 30 m resolution) NASA Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) distributed by OpenTopography (Nasa JPL, 2013) was used to calculate the mean elevation of each grid cell. Grids with a mean elevation exceeding 1,700 m were excluded from the analysis.

The remaining grids—defined hereafter as the effective suitable habitat area—formed the spatial domain to which all subsequent coordinate-based analyses were restricted. The total area of suitable habitat following both filtering steps was 1,399 km².

2.5. Data Analysis

All statistical computations and spatial processing were performed in QGIS (Version 3.22.9; QGIS Development Team 2025) and R (Version 4.4.1; R Core Team 2025), with breakpoint detection conducted using the *segmented* package.

2.5.1. Specimen-based Establishment Phase Analysis

To mitigate the sampling-effort bias inherent in opportunistic herbarium records, the annual *collection rate* was computed by dividing the number of *H. radicata* specimens by the total number of vascular plant specimens collected on the Jeju Island in the same year (Aikio et al. 2010):

$$Collection\ Rate_{\ t} = n_{H.\ radicata,\ t} / n_{total,\ t}$$

The collection rate was calculated for each calendar year *t*.

The annual collection rates were transformed into a cumulative collection rate to minimize annual stochasticity and capture the long-term invasion trajectory, which served as the response variable for the time-series modeling.

The analytical framework was structured around two complementary procedures. **First**, a sensitivity analysis was conducted to assess the impact of sampling pulses. The 2014 record was identified as a potential outlier driven by an anthropogenic contraction of survey effort (n = 166 records, ~ 10% of the 1981–2013 annual average of ~ 1,670 records). To evaluate the robustness of the inferred breakpoint against this anomaly, two scenarios were constructed: Scenario 1 (inclusive of all 1981–2014 records) and Scenario 2 (exclusive of the 2014 record). **Second**, competitive model selection was performed to validate the presence of a lag phase. The cumulative collection rate was fitted using piecewise linear (segmented) regression, which detects structural breaks in the cumulative trajectory over time (Larkin 2012). The segmented model was tested against a parsimonious exponential growth model and a simple linear model. Model selection was based on the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC), with the lowest information loss indicating the optimal fit (Figure S1).

The temporal breakpoint, representing the transition from establishment to expansion, was estimated together with its 95% confidence interval (CI). To statistically confirm the non-constancy of the invasion rate across the identified segments, Davies' test was performed to verify a significant difference in the slope parameters before and after the estimated breakpoint.

2.5.2. Coordinate-based Spatial Dynamics Analysis

To quantify the spatial expansion dynamics of *H. radicata*, a count-based effort correction was first applied at the coordinate level. The annual *detection rate* was defined as the ratio of unique *H. radicata* occurrence coordinates to the total number of unique survey coordinates recorded within the effective suitable habitat area (described in Section 2.4.2) for each year. When multiple occurrences or survey records were located at the same coordinate within a single year, they were treated as a single binary indicator of survey performance for that point-year to prevent overestimation of spatial occupancy. To avoid false-lag effects (Hyndman et al. 2015), years between 2004 and 2010—when no valid surveys were recorded within the effective suitable habitat area—were assigned NA values. This established a standardized time series anchored to the 2003 baseline and the continuous records from 2011 onward.

The annual detection rate was then converted to the Effective Range Radius (ERR), using the theoretical framework described by Ward et al. (2020). The ERR linearizes the movement of the invasion front: while occupied area typically grows quadratically over time, the equivalent radius grows linearly, providing a more sensitive metric for detecting subtle shifts in expansion velocity (km $year^{-1}$). The ERR was derived through the following sequential steps:

(i) Annual occupied area was estimated as the product of the annual detection rate and the total effective suitable habitat area:

$$A_t = Detection\ Rate_t \times A_{suitable}$$

(ii) Cumulative occupied area was obtained by sequential summation:

$$A_T = \Sigma_{t \le T} A_t$$

(iii) ERR was calculated by treating the cumulative occupied area as a single virtual circle:

$$ERR_T = \sqrt{(A_T / \pi)}$$

(iv) Annual expansion velocity (km $year^{-1}$) was computed as the temporal derivative of ERR between consecutive years:

$$v_t = ERR_t - ERR_{t-1}$$

Statistical analysis was restricted to years where *H. radicata* occurrences were confirmed within the effective suitable habitat area (2003 and the continuous period from 2011 to 2022). Given the multi-phased nature of the invasion of this species on the Jeju Island, a two-breakpoint segmented regression model (Ni 2023) was applied to the ERR time-series to identify two critical ecological transitions: (i) the inflection point marking the shift from the initial lag phase to rapid expansion (acceleration), and (ii) the onset of the stabilization phase, where the expansion rate plateaus due to habitat saturation. The model was fitted by minimizing the residual sum of squares (RSS) to estimate the optimal location of the two breakpoints. To verify the statistical significance of the change in slopes at each transition, Davies' test was performed, and the temporal bounds and uncertainty of these transitions were quantified using 95% confidence intervals.

2.5.3. Text Mining and Semantic Network Analysis

To quantitatively trace the temporal evolution of policy discourse across the four temporal phases (retrospectively defined in Section 3.3) based on the biological inflection points identified in Sections 3.1.1 and 3.1.2, text mining and semantic network analysis (SNA) were conducted in R (R Core Team 2025). The textual data underwent a rigorous preprocessing pipeline in accordance with tidy data principles (Silge and Robinson 2016). Initially, noise was eliminated through an extended custom stop-word dictionary, removing functionally irrelevant terms, syntactic remnants, and journalistic filler words

such as "pointed out," "added," "removal," and "full-scale." Subsequently, nomenclature was standardized into English scholarly terms to ensure international accessibility and analytical consistency. For instance, institutional terms were unified under "EDS" or "Eradication project," and various syntactic forms of expansion were merged into "Spread." Regional descriptors were appended with a "(Region)" tag to improve contextual clarity for international readers, with the exception of the term "Inland."

Following preprocessing, a Term Frequency–Inverse Document Frequency (TF–IDF) analysis was performed to identify phase-specific keywords representing the dominant issues of each period (Manning et al. 2008). This statistical algorithm penalizes universally common terms while assigning higher mathematical weights to keywords that distinguish the core discourse of a specific invasion phase (Silge and Robinson 2016). To elucidate the structural connectivity of these discourses, SNA was performed based on keyword co-occurrence within the documents (Doerfel 1998). Network topological structure was visualized using the *igraph* (Csardi and Nepusz 2006) and *ggraph* (Pedersen 2025) packages. To accurately reflect policy fragmentation, isolated nodes—terms with high TF–IDF scores but zero co-occurrence—were deliberately retained. The final network layout was mapped using the Kamada–Kawai algorithm (Kamada and Kawai 1989), with a minimal constant applied to isolated nodes to ensure their stability and visibility within the analytical space. Furthermore, label repulsion and plot margins were optimized to maintain textual clarity for standardized English terms, ensuring legibility independently of frequency-based centrality metrics.

2.5.4. Integrated Cross-validation Analysis

To ensure the consistency of the identified invasion trajectory, an integrated analysis was performed by synchronizing the temporal results of the specimen-based establishment phase (Section 2.5.1) with the spatial expansion metrics derived from the coordinate-based analysis (Section 2.5.2) and the discursive shifts captured by text mining (Section 2.5.3). The statistical framework for the integrated analysis follows the same logic as segmented regression described in Sections 2.5.1 and 2.5.2, and cross-validates the inferred biological inflection points using a multi-proxy approach.

3. Results

3.1. Integrated Invasion Dynamics of *H. radicata* on the Jeju Island

The invasion of *H. radicata* on the Jeju Island represents a multi-decadal progression from initial establishment to comprehensive regional saturation. This process was analyzed through two complementary lenses: Temporal specimen accumulation and spatial range expansion.

3.1.1. Specimen-based Temporal Growth and Establishment

The invasion trajectory of *H. radicata* on the Jeju Island followed a distinct biphasic progression, as evidenced by the long-term integration of herbarium specimens and spatial coordinate data (Fig. 1). Temporal analysis of the establishment phase revealed that the species underwent a protracted lag phase before transitioning into a period of rapid demographic expansion. Specifically, the segmented regression model identified a statistically significant temporal breakpoint (Davies' test, $p < 0.0001$) in 2006.6 (95% CI: 2004.9–2008.3), marking the formal biological termination of the establishment phase.

Prior to this inflection point, the cumulative collection rate increased at a negligible slope of 0.0008. However, following the breakpoint, the rate of increase escalated sharply to 0.0061, representing a nearly 8-fold acceleration in collection frequency. This divergence provides empirical evidence that the species had achieved successful biological establishment and initiated active expansion approximately 4 years prior to its formal legal designation as an EDS in 2009 (Fig. 1A). This discrepancy highlights a critical temporal gap between biological reality and administrative intervention.

3.1.2. Coordinate-based Spatial Expansion and Habitat Saturation

The time-series analysis of the ERR provides a macro-scale quantification of the invasion trajectory, delineating a clear progression toward regional saturation that transcends simple occurrence frequency (Fig. 1B). Using a two-breakpoint segmented regression model, the spatial trajectory was categorized into three distinct phases representing a completed invasion cycle.

The first structural breakpoint (Break 1) was identified at 2008.7 (95% CI: 2006.0–2011.3). Although the statistical significance of this shift approached the conventional alpha threshold (Davies' test $p = 0.0504$), it establishes a mathematically sound demarcation between the initial lag and the subsequent explosive acceleration. During the initial lag phase (Phase 1), expansion velocity remained effectively stagnant at 0.0000 km/year, reflecting a period of localized persistence or limited detection probability primarily attributed to temporal data gaps in survey records between 2003 and 2011. Following this inflection, the expansion velocity surged to 0.7557 km/year during the acceleration phase (Phase 2). This abrupt escalation was highly synchronized with the institutional shift following the 2009 EDS designation, prompting an intensification of survey efforts (e.g., $n = 569$ in 2011; Figure S2). This temporal alignment reinforces the identification of Break 1 as a sampling-induced inflection point, driven by a sudden influx of spatial records after a prolonged period of data scarcity.

The trajectory subsequently reached a second structural breakpoint (Break 2) at 2018.7 (95% CI: 2015.6–2021.8), signaling the onset of the stabilization phase (Phase 3). During this terminal stage, expansion velocity significantly decelerated to 0.0490 km/year—a 15-fold reduction compared to the preceding acceleration phase. The resulting plateau indicates that *H. radicata* has effectively approached its ecological carrying capacity on the Jeju Island, having occupied the majority of available climatically and ecologically suitable habitats. In synthesis, while the specimen-based analysis accurately captured the fundamental biological termination of the establishment phase in 2006.6, the coordinate-based ERR analysis provides an integrated view of the subsequent expansion and eventual regional saturation in

2018.7. These complementary findings provide empirical evidence of a completed four-decade invasion cycle, transitioning from cryptic establishment to comprehensive habitat saturation across the island's ecosystem (Fig. 1B).

3.2. Sensitivity Analysis of Establishment Phase and Model Selection

To evaluate the robustness of the identified invasion trajectory, a sensitivity analysis was performed by comparing two scenarios that differ in the inclusion of a potential sampling outlier in 2014. Scenario 1, which integrated the complete dataset, detected a significant structural break in the establishment dynamics (Fig. 2A). Under this baseline scenario, the termination of the temporal lag phase was estimated at 2006.6 (95% CI: 2004.9–2008.3), where the cumulative collection rate, as previously described, transitioned from an initial slope (0.0008) to an expansion slope (0.0061) (Davies' test, $p < 0.0001$).

However, a detailed examination of the annual records revealed a disproportionate spike in the 2014 collection rate (0.042), driven primarily by a precipitous contraction in survey effort rather than a biological surge. Specifically, the botanical survey effort in 2014 was limited to 166 records, representing only 10% of the annual average effort (~ 1,670 records) maintained between 1981 and 2013. While the average annual target count for *H. radicata* was 1.4 individuals during the pre-2014 period, recording 7 individuals against this severely diminished total effort (N_{effort} = 166) generated an artificially inflated rate (Table S1). To mitigate this sampling artifact, Scenario 2 was conducted by excluding the 2014 data point (Fig. 2B). This refined model estimated the lag-phase termination at 2004.9 (95% CI: 2003.8–2006.0; Davies' test, $p < 0.0001$), with an expansion slope of 0.0036. Although removing the outlier led to a slight advancement of the breakpoint (~ 1.7 years), the 95% confidence intervals exhibit substantial overlap. This consistency indicates that the identified establishment dynamics remain fundamentally stable despite temporary sampling anomalies.

Furthermore, comparative model selection clarified the underlying nature of the invasion dynamics. In the presence of the 2014 sampling artifact (Scenario 1), the non-linear exponential growth model (AIC = -256.0; BIC = -251.4) exhibited a marginally better statistical fit than the segmented regression model (AIC = -252.5; BIC = -244.9) (Figure S1A), likely because the outlier artificially smoothed this abrupt transition. However, when this confounding survey anomaly was excluded (Scenario 2), the segmented model (AIC = -311.0; BIC = -303.5) significantly outperformed the exponential alternative (AIC = -306.1; BIC = -301.6) (Figure S1B). This confirms that the fundamental biological trajectory of *H. radicata* is distinctly step-wise—characterized by a protracted lag phase followed by a sudden expansion—and that the temporary exponential fit was merely a statistical artifact driven by the disproportionate sampling rate in 2014. Crucially, because retaining the complete dataset (Scenario 1) did not introduce systemic bias into the estimation of the primary biological inflection point (as evidenced by the overlapping 95% CIs across scenarios), artificially truncating the empirical record is statistically unwarranted. These

findings justify utilizing the comprehensive dataset for subsequent administrative asynchrony analysis, demonstrating that the established biological timeline is robust against isolated survey fluctuations.

3.3. Evolution of Multi-phased Policy Discourse

To trace the temporal evolution of public and policy discourse surrounding *H. radicata* on the Jeju Island, 71 news articles published between 1999 and 2025 were analyzed using a 2-stage analytical sequence—TF–IDF for phase-specific keyword isolation and SNA for evaluating shifts in contextual coupling and structural connectivity (Table S2). Based on the biological inflection points identified in Sections 3.1.1 and 3.1.2, this corpus was retrospectively organized into four temporal phases: Phase 1 (1999–2005; n = 7), corresponding to the biological lag phase prior to the acceleration point identified at 2006.6; Phase 2 (2006–2009; n = 14), spanning from the onset of biological acceleration through the formal EDS designation in June 2009; Phase 3 (2010–2018; n = 20), covering the post-designation period of sustained spatial expansion up to the stabilization point identified at 2018.7; and Phase 4 (2019–2025; n = 30), corresponding to the regional saturation phase characterized by chronic management dependency. The temporal distribution of the corpus—with article frequency increasing progressively across phases—quantitatively reflects the growing institutional attention accompanying the biological trajectory of the species.

In Phase 1 (1999–2005), the discursive landscape was characterized by administrative initiation, with keywords such as *Initiation* and *Necessity* yielding the highest TF–IDF scores (Fig. 3A). The corresponding structural network revealed a fragmented discourse where planning-related clusters remained decoupled from operational ecological threats, such as *Occupation*, signifying a lack of cohesive management integration during the initial lag phase (Fig. 3B). Phase 2 (2006–2009) marked a transition toward institutional formalization, dominated by the prominence of *Legal designation* (Fig. 3A). However, SNA visualized a persistent structural gap between institutional-scientific clusters and critical geographic defense zones, specifically *Mt. Halla* (Fig. 3B). This decoupling indicates that while legal frameworks were established, they failed to incorporate site-specific risk communication into a unified discursive domain.

During Phase 3 (2010–2018), following the designation of *H. radicata* as an EDS, discourse shifted toward spatial expansion, with *Udo Island* and *Potential* emerging as dominant themes (Fig. 3A). The network evolved into elongated chains, reflecting the real-time tracking of geographical spread and the operational involvement of regional agencies, such as the *Yeongsangang BEO* (Fig. 3B). By Phase 4 (2019–2025), however, the discourse became saturated with chronic management constraints, specifically *Eradication project* and *Management cost* (Fig. 3A). Notably, the absolute TF–IDF scores in this stage were significantly lower than in all preceding phases.

This qualitative shift is visually corroborated by the marked increase in isolated nodes within the semantic network. While the *Eradication project* remains a relational hub, foundational ecological concepts have been marginalized into isolated positions, indicating a lack of contextual coupling of these concepts with management actions (Fig. 3B). Consequently, contemporary discourse has

collapsed into a reactive cycle of localized, cost-intensive limits, presenting a structural barrier to the development of integrated, long-term ecological restoration strategies.

4. Discussion

4.1. Invasion trajectory and lag-phase characterization

The specimen-based analysis identified a biologically significant inflection point at 2006.6 (95% CI: 2004.9–2008.3; Davies' test, $p < 0.0001$), marking the formal termination of a protracted lag phase that persisted for approximately 25 years following the presumed introduction of *H. radicata* to the Jeju Island in the early 1980s. This lag duration is notably shorter than the mean lag phase of 47.3 ± 34.6 years reported by Larkin (2012) for upper-Midwest plant invaders, suggesting that the biological attributes of *H. radicata*—specifically its high phenotypic plasticity, dual wind- and animal-mediated dispersal mechanisms, and capacity for both photoblastic and scotoblastic germination—facilitated its atypically rapid transition from cryptic establishment to explosive range expansion (Mitchell and Bakker 2014; Lee et al. 2024). This interpretation has been independently corroborated by field investigations conducted by the National Institute of Environmental Research immediately following the identified inflection point: surveys in 2006–2007 documented near-monospecific dominance of *H. radicata* on the Jeju Island, with an average coverage of 66.7% and a density of 286.7 individuals m^{-2} (Ha 2006)—a ground-truth observation that is fully consistent with a population that had crossed its biological acceleration threshold by 2006.6.

The abrupt transition in the collection rate slope—from 0.0008 to 0.0061 per year, representing an approximately eight-fold acceleration—reflects a fundamental shift in the species' demographic dynamics, consistent with its release from density-dependent constraints that characteristically terminate the lag phase (Crooks 2005; Aikio et al. 2010). Prior to this inflection, the cumulative collection rate increased at a rate indistinguishable from statistical noise, a pattern characteristic of the cryptic establishment stage in which populations are too sparse and spatially restricted to generate detectable botanical signals (Crooks and Soulé 1999; Hyndman et al. 2015). The robustness of this inflection point was confirmed through sensitivity analysis (as described in Section 3.2): when the 2014 sampling anomaly was excluded (Scenario 2), the breakpoint shifted only marginally to 2004.9 (95% CI: 2003.8–2006.0), with the 95% confidence intervals of both scenarios exhibiting substantial overlap. Notably, *H. radicata*'s true biological transition may have preceded our primary estimate of 2006.6, as the cumulative regression approach is known to produce conservative breakpoint estimates due to under-recording of weedy taxa during their low-density lag phases (Larkin 2012; Hyndman et al. 2015).

Complementing this temporal analysis, the coordinate-based ERR analysis delineated the subsequent spatial trajectory, identifying a stabilization breakpoint at 2018.7 (95% CI: 2015.6–2021.8). The progression from 0.0000 km yr^{-1} during the survey-limited period to a peak expansion velocity of 0.7557 km yr^{-1}, followed by a 15-fold deceleration to 0.0490 km yr^{-1} after 2018.7, provides compelling evidence that *H. radicata* has effectively reached its ecological carrying capacity on the Jeju Island. This spatial

saturation, occurring approximately 35 years after its presumed introduction and 12 years after the biological inflection point identified in the present study, is consistent with the finite-area constraints characteristic of insular ecosystems (Son et al. 2023), suggesting that the species has now occupied the substantial majority of climatically and ecologically suitable habitats within the island's effective range.

4.2. Temporal asynchrony between social recognition and biological dynamics

Contrary to our initial hypothesis (H1), which predicted that social recognition may temporally align with the biological expansion phases of *H. radicata*, our results reveal that media discourse emerged substantially prior to the biological acceleration point. News media coverage of the species on the Jeju Island was first documented in 1999—approximately 7 years before the identified biological inflection point of 2006.6—while the species was still in its lag phase. Rather than representing a failure of our hypothesis, this unexpected finding constitutes a substantively important result: it demonstrates that insular ecosystems with high conservation awareness can generate social visibility signals even during the cryptic, low-density lag phase, representing a more sensitive socio-ecological detection system than is typically assumed in mainland invasion contexts (Crooks 2005; Moon 2015; IPBES 2023).

This early social detection can be attributed to two reinforcing factors unique to the context of Jeju Island. First, the geographical isolation and finite land area of the island serve to amplify the perceived conspicuousness of alien plants relative to mainland settings, where spatial dilution reduces social visibility. Second, Jeju's internationally recognized conservation status as a UNESCO Biosphere Reserve, World Natural Heritage Site, and Global Geopark, generates a heightened social sensitivity toward ecological anomalies, effectively lowering the social visibility threshold (Crooks 2005) at which a species enters public discourse. These contextual factors likely explain why Phase 1 (1999–2005) discourse was already characterized by keywords such as *Ecosystem Destruction* and *Concerns regarding Spread*, despite the species being in its biological lag stage.

However, the temporal evolution of discourse across phases reveals a critical structural decoupling between social recognition and institutional effectiveness. The transition from Phase 2 (2006–2009) to Phase 3 (2010–2018) exposes a persistent disconnect: while the species initiated sharp biological acceleration at 2006.6 (slope = 0.0061), formal institutionalization through EDS designation was delayed until 2009, forcing subsequent policy discourse into a reactive tracking mode (Epanchin-Niell 2017). During Phase 3, although expansion velocity peaked at 0.7557 km yr^{-1}, policy discourse remained spatially localized to high-value ecological assets such as *Udo Island* and *Mt. Halla*, reflecting a defensive posture that concentrated management resources on protecting symbolic biodiversity hotspots rather than addressing island-wide expansion that had already breached the biological establishment threshold (Moon 2015).

By Phase 4 (2019–2025), this governance gap had culminated in a state of chronic management dependency, mirroring the spatial stabilization identified at 2018.7. The marked decline in absolute TF–IDF scores and the proliferation of isolated nodes within the semantic network during this phase signify

not merely a quantitative reduction in discourse but a qualitative collapse of integrated strategic thinking—a state of high discursive entropy wherein the strategic core has dissipated, leaving a fragmented network focused on repetitive fiscal concerns and localized routine removal tasks. This structural deterioration of public discourse directly reflects the systemic "knowing-doing gap" (Esler et al. 2010): despite the early social warnings that surfaced during Phase 1, formal institutional intervention was delayed until the species had effectively transitioned through its entire invasion cycle to a state of regional saturation.

4.3. Policy timeliness and the administrative lag

Our results provide clear support for our second hypothesis (H2): the 2009 EDS designation followed both the onset of social recognition and the biological acceleration point by substantial temporal margins, confirming significant asynchrony between institutional action and the underlying biological and social dynamics. The present study identifies two analytically distinct temporal gaps that together constitute the observed administrative lag. The first is a biological-policy gap of approximately 2.4 years, spanning from the biological inflection point (2006.6) to the designation of *H. radicata* as an EDS (June 2009)—a period wherein the species was already in explosive expansion. The second is a broader socio-regulatory gap of approximately 10 years, spanning from the emergence of media discourse in 1999 to formal legal designation in 2009. From the presumed introduction of the species in the 1980s to regulatory action, the total introduction-to-regulation lag approaches 20 years—a timeline that encapsulates the full spectrum of this policy asynchrony.

Critically, the 2009 designation was implemented only after the species had already surpassed its biological inflection point and entered a phase of rapid acceleration. The institutional void during this period was not a consequence of ecological invisibility, as demonstrated by the early media coverage beginning in 1999 and the field investigations conducted by NIER in 2006–2007 (Ha 2006; Kil 2007), but rather of structural barriers within the national biosecurity framework. Notably, both NIER reports recommended that the EDS designation be restricted to specific habitat types such as montane grasslands and conservation-priority herbaceous habitats, rather than implemented as a uniform nationwide listing (Ha 2006; Kil 2007). The actual 2009 designation, implemented under Ministry of Environment Ordinance No. 332, adopted the latter approach without the stage- and region-specific differentiation that the scientific evidence at the time supported, underscoring the disconnect between scientific recommendations and policy design that characterizes systemic "knowing-doing gaps" (Esler et al. 2010; Ahmed et al. 2022).

Three interacting factors can be identified as primary drivers of this administrative lag. First, institutional fragmentation and geographical distance severely hindered a rapid response. Regulatory authority during the initial invasion phases was divided between the Yeongsan River Basin Environmental Office—physically located in Gwangju on the Korean mainland—and the Jeju local government, blurring lines of responsibility and resulting in the absence of species-specific management guidelines (Genovesi and Shine 2004; Piria et al. 2017). Second, this administrative inertia reflects a systemic vulnerability in the national biosecurity framework rather than an isolated botanical anomaly (Simberloff et al. 2013). An

institutional delay paralleling this is evident in the management of the Asian yellow-legged hornet (*Vespa velutina*); despite its ecological risks being documented as early as 2003, its designation as an EDS was not granted until 2019, by which point the species had achieved nationwide saturation (Kim et al. 2006; Choi et al. 2012). Such recurring lags across taxonomically distinct invasive species demonstrate the persistent structural failures in translating scientific and social evidence into timely legal intervention. Third, cognitive normalization acted as a psychological barrier: having been present on the Jeju Island since the 1980s, *H. radicata* became colloquially known as Gaemindeulle, leading the public to perceive it as a familiar, benign weed, thereby suppressing social demand for its eradication during the critical optimal control window (Sharp et al. 2011).

4.4. Management implications and the cost of inaction

The temporal asynchrony documented in the present study has translated directly into a permanent transition from a potentially eradicable introduction to a state of chronic management dependency—a trajectory exemplifying the "cost of inaction" framework (Ahmed et al. 2022). As the window for cost-effective, proactive eradication during the low-density lag phase of the 1990s was missed, *H. radicata* now occupies a majority of suitable habitats across the Jeju Island and has achieved regional stabilization. As absolute eradication is no longer a viable ecological or economic goal following this spatial saturation, the Jeju Island is now burdened with the economic and ecological costs of permanent reactive management—costs that global evidence indicates are at least 25 times greater than those of proactive biosecurity (Cuthbert et al. 2022).

According to strategic management models, the efficacy of invasive species intervention is strictly stage-dependent: proactive eradication is viable only during the low-density lag phase, whereas containment and impact mitigation become the inevitable, yet markedly less efficient responses once a population surpasses the biological inflection point (Mehta et al. 2007; Blackburn et al. 2011). The current management of *H. radicata* on the Jeju Island, characterized by annual biomass removal events concentrated during the May–June flowering season, is structurally constrained by the absence of species-specific management protocols and a heavy reliance on local municipal governments (Kim and Koo 2021). This approach reflects a forced shift toward a maintenance paradigm in which finite resources are expended on routine, non-systematic removal rather than on strategic, outcome-based ecological restoration.

The discourse during Phase 4, dominated by Management cost and Eradication project as repetitive focal terms, quantitatively mirrors this transition to chronic management dependency. The collapse of integrated strategic discourse—evidenced by the proliferation of isolated nodes in the Phase 4 semantic network—indicates that the current policy environment lacks the conceptual infrastructure required for transitioning from reactive biomass removal to evidence-based, stage-specific management. This underscores the urgent necessity of a standardized Early Detection and Rapid Response framework utilizing diverse evidence streams, including media discourse trends, citizen science observations, and botanical survey rates, as early-warning triggers for legislative action, capable of bridging the gap

between initial social perception and decisive institutional intervention (Kim and Koo 2021; Ahmed et al. 2022).

4.5. Limitations and multi-proxy robustness

Some methodological limitations inherent to our multi-proxy dataset should be explicitly acknowledged. First, the use of cumulative collection rates in the specimen-based analysis results in a known statistical vulnerability: autocorrelation in a cumulative time series can generate artefactual lag-phase signals, and the conservative nature of breakpoint estimates derived from cumulative regression may bias the inferred inflection point toward later years relative to the true ecological transition (Hyndman et al. 2015). This conservative bias, however, strengthens rather than weakens our central argument: if the true biological inflection preceded 2006.6, the temporal gap between biological dynamics and the 2009 policy designation would be correspondingly greater than reported. Second, the opportunistic nature of herbarium records introduces inherent collector bias. Weedy taxa such as *H. radicata* are systematically under-recorded during their low-density lag phases relative to their actual population trajectory (Aikio et al. 2010; Larkin 2012). The present study addressed potential false-lag effects through the application of a collection rate correction and the sensitivity analysis presented in Section 3.2, which confirmed the robustness of the identified breakpoint across different sampling scenarios.

Third, the coordinate-based dataset spans only 8 survey years (2003, 2011, 2013, 2015, 2017, 2020, 2021, 2022), with a notable absence of surveys between 2004 and 2010. It is critical to clarify that this data gap reflects the absence of systematic botanical surveys during this period, rather than the confirmed biological absence of *H. radicata*. This distinction is methodologically consequential: years lacking valid surveys were systematically assigned NA values in order to maintain analytical rigor and prevent speculative interpolation, and should not be interpreted as evidence that the species was absent from suitable habitats during this interval. The historical evolution of ecological monitoring in South Korea, which achieved institutional rigor for high-resolution, species-specific surveillance primarily after the late 2000s (Yun and Shin 2015; Moon 2015), explains the fragmented nature of the early coordinate record as a systemic feature of Korean ecological surveillance rather than a specific methodological failure (Kang et al. 2023). Fourth, the news media corpus (n = 71) was small and unevenly distributed across phases (n = 7 to 30), limiting the statistical power of network-level inferences, particularly for Phase 1. The quantitative network metrics (density, modularity, betweenness centrality) reported for each phase should be interpreted with appropriate caution regarding small-sample stability.

Nevertheless, the robustness of our findings is reinforced by the convergence of three independent evidence streams. The integration of herbarium records, spatial coordinates, and news media discourse identifies a consistent biological-social-institutional timeline that transcends the constraints of any single data source. Following the analytical logic postulated by Ward et al. (2020) and Ni (2023), the use of ERR and semantic network analysis provides more sensitive detection of expansion-phase transitions than conventional area-based metrics. This multi-proxy framework demonstrates that even with incomplete historical datasets, the convergent signals across evidence streams are sufficient to characterize the fundamental temporal structure of the invasion and the corresponding institutional

response. Future studies should prioritize the integration of genetic data (Lee et al. 2024) and high-resolution remote sensing imagery to further constrain the timing and spatial dynamics of the biological inflection point identified here.

5. Conclusion

This study elucidates the temporal asynchrony between biological spread, social perception, and institutional response through a 40-year longitudinal analysis of *Hypochaeris radicata* on the Jeju Island. Our findings reveal that news media functioned as an effective "social sensor," detecting ecological threats as early as 1999—7 years prior to the biological inflection point in 2006. However, the formal administrative response was delayed by two decades, with the legal designation of the species as an EDS occurring only in 2009. This historical lag provides empirical evidence of the "management paradox," where the embryonic stage of past regulatory frameworks led to the loss of critical windows for cost-effective eradication.

As Kim and Koo (2021) suggest, South Korea's invasive species governance has undergone a profound evolution from a fragmented framework under the historical *Wildlife Protection Act*—which primarily prioritized agricultural pests and rare species—to a more systematized ecosystem-based approach that culminated in the formal EDS category in 2009. Currently, this system has reached considerable technical maturity, as evidenced by *the Act on the Conservation and Use of Biological Diversity*, which mandates a streamlined, professional 1-year evaluation period for candidate species (Ministry of Climate, Energy and Environment, 2025). However, a critical "implementation gap" persists: the framework remains disproportionately focused on the administrative act of designation, lacking a statutory mandate for post-listing operational roadmaps. Consequently, enhanced assessment expertise does not always translate into effective field-level control.

To bridge this "implementation gap" and prevent the accumulation of future "invasion debt," we propose a three-step policy reform:

First, the institutionalization of social sensors. Legislative triggers should be established to initiate official risk assessments when social perception thresholds—monitored via media discourse or citizen science—indicate a significant shift, thereby capturing "sleeper species" before they enter the rapid expansion phase.

Second, the mandate of post-designation roadmaps. Legal listing should be viewed as an operational starting point rather than an administrative conclusion. We recommend a statutory requirement to establish species-specific standard operating procedures and budget allocations within six months of designation to eliminate the administrative silence observed in historical cases.

Third, the adoption of spatially-explicit management standards. Following the framework of Osawa et al. (2019), management strategies must be differentiated based on distribution density; specifically,

prioritizing "total eradication" for pioneer populations on the invasion front while implementing "long-term containment" for core established populations.

In conclusion, while South Korea has successfully modernized its species evaluation expertise, the next frontier of biosecurity lies in synchronizing this expertise with mandatory execution. By integrating social awareness with rapid, statutory roadmaps, policy-makers can transform a reactive bureaucracy into a proactive system capable of outpacing biological acceleration.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Sangsun Lee and Hyerin Yu. The first draft of the manuscript was written by Sangsun Lee and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethical Approval

No ethical approval was required for this study as it did not involve human or animal subjects.

Informed Consent

Not applicable.

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References

1. Ahmed DA, Hudgins EJ, Cuthbert RN, Kourantidou M, Diagne C, Haubrock PJ, Leung B, Liu C, Leroy B, Petrovskii S, Beidas A, Courchamp F (2022) Managing biological invasions: The cost of inaction. Biol

Invas 24(7):1927–1946. https://doi.org/10.1007/s10530-022-02755-0

2. Aikio S, Duncan RP, Hulme PE (2010) Lag-phases in alien plant invasions: Separating the facts from the artefacts. Oikos 119(2):370–378. https://doi.org/10.1111/j.1600-0706.2009.17963.x
3. An YH (2001) A study on the vegetation of pasture and distribution of exotic plants on Jeju Island. Master's thesis, Jeju National University, Jeju, Republic of Korea
4. Blackburn TM, Pyšek P, Bacher S, Carlton JT, Duncan RP, Jarošík V, Wilson JRU, Richardson DM (2011) A proposed unified framework for biological invasions. Trends Ecol Evol 26(7):333–339. https://doi.org/10.1016/j.tree.2011.03.023
5. Choi MB, Martin SJ, Lee JW (2012) Distribution, spread, and impact of the invasive hornet Vespa Velutina in South Korea. J Asia Pac Entomol 15(3):473–477. https://doi.org/10.1016/j.aspen.2011.11.004
6. Crooks JA (2005) Lag times and exotic species: The ecology and management of biological invasions in slow-motion. Écoscience 12(3):316–329. https://doi.org/10.2980/i1195-6860-12-3-316.1
7. Crooks JA, Soulé ME (1999) Lag times in population explosions of invasive species: Causes and implications. In: Sandlund OT, Schei PJ, Viken Å (eds), Invasive species and biodiversity management. Springer Netherlands, p 103–125. https://doi.org/10.1007/978-94-011-4523-7_7
8. Csardi G, Nepusz T (2006) The igraph software package for complex network research. In InterJournal: Vol. Complex Systems (p. 1695). https://igraph.org
9. Cuthbert RN, Diagne C, Hudgins EJ, Turbelin A, Ahmed DA, Albert C, Bodey TW, Briski E, Essl F, Haubrock PJ, Gozlan RE, Kirichenko N, Kourantidou M, Kramer AM, Courchamp F (2022) Biological invasion costs reveal insufficient proactive management worldwide. Sci Total Environ 819. https://doi.org/10.1016/j.scitotenv.2022.153404. :Article 153404
10. Diagne C, Leroy B, Vaissière AC, Gozlan RE, Roiz D, Jarić I, Salles JM, Bradshaw CJA, Courchamp F (2021) High and rising economic costs of biological invasions worldwide. Nature 592(7855):571–576. https://doi.org/10.1038/s41586-021-03405-6
11. Doerfel ML (1998) What constitutes semantic network analysis? A comparison of research and methodologies. Electron J Commun 8(2)
12. Duncan RP (2021) Time lags and the invasion debt in plant naturalisations. Ecol Lett 24(7):1363–1374. https://doi.org/10.1111/ele.13751
13. Epanchin-Niell RS (2017) Economics of invasive species policy and management. Biol Invas 19(11):3333–3354. https://doi.org/10.1007/s10530-017-1406-4
14. Esler KJ, Prozesky H, Sharma GP, McGeoch M (2010) How wide is the knowing-doing gap in invasion biology? Biol Invas 12(12):4065–4075. https://doi.org/10.1007/s10530-010-9812-x
15. Genovesi P, Shine C (2004) European strategy on invasive alien species (Nature and Environment No. 137). Council of Europe Publishing

16. Gleason HA, Cronquist A (1991) Manual of vascular plants of northeastern United States and adjacent Canada, 2nd edn. The New York Botanical Garden. https://doi.org/10.21135/893273651.001
17. Ha SB (2006) Precise investigation of invasive alien species with high ecological risk and the status of designation of ecosystem-disturbing species in advanced countries (I). Report. National Institute of Environmental Research, Ministry of the Environment, Republic of Korea
18. Hyndman RJ, Mesgaran MB, Cousens RD (2015) Statistical issues with using herbarium data for the estimation of invasion lag-phases. Biol Invas 17(12):3371–3381. https://doi.org/10.1007/s10530-015-0962-8
19. IPBES (2023) Summary for policymakers of the thematic assessment report on invasive alien species and their control of the Intergovernmental Science-Policy Platform on biodiversity and Ecosystem Services Roy HE (eds). *IPBES secretariat*. https://doi.org/10.5281/zenodo.7430692
20. Kamada T, Kawai S (1989) An algorithm for drawing general undirected graphs. Inf Process Lett 31(1):7–15. https://doi.org/10.1016/0020-0190(89)90102-6
21. Kang D, Park G, Choi SS, Yi TW (2023) Characteristics Citizen Participation National Ecosystem Survey Data. GEO Data 5(4):321–329. https://doi.org/10.22761/GD.2023.0038
22. Khuroo AA, Reshi ZA, Malik AH, Weber E, Rashid I, Dar GH (2012) Alien flora of India: Taxonomic composition, invasion status and biogeographic affinities. Biol Invas 14(1):99–113. https://doi.org/10.1007/s10530-011-9981-2
23. Kil JH (2007) Precise investigation of invasive alien species with high ecological risk and management plan (II), Report. National Institute of Environmental Research, Ministry of the Environment, Republic of Korea
24. Kim DB, Koo AK (2021) A study on the current status and improvement of management of ecosystem-disturbing species. J Environ Impact Assess 30(6):461–477. https://doi.org/10.15301/jepa.2021.29.4.59
25. Kim HH, Mizuno K, Kim DB, Lee HS, Kong WS (2020) Distribution of invasive alien plants in island areas of the Korean Peninsula based on flora data. Korean J Environ Biol 38(3):392–403. https://doi.org/10.11626/KJEB.2020.38.3.392
26. Kim J-K, Choi MB, Moon T-Y (2006) Occurrence of *Vespa Velutina* Lepeletier from Korea, and a revised key for Korean *Vespa species* (Hymenoptera: Vespidae). Entomol Res 36(2):112–115. https://doi.org/10.1111/j.1748-5967.2006.00018.x
27. Korea national arboretum (2025) Korea Biodiversity Information System. *Accessed* December 10, 2025. http://www.nature.go.kr
28. Korean Statistical Information Service (KOSIS) (2024) Statistical Database of the Republic of Korea. *Statistics Korea*. https://kosis.kr/
29. Kowarik I (1995) Time lags in biological invasions with regard to the success and failure of alien species. In: Pyšek P, Prach K, Rejmánek M, Wade M (eds) Plant invasions: General aspects and special problems. SPB Academic Publishing, pp 15–38

30. Larkin DJ (2012) Lengths and correlates of lag phases in upper-Midwest plant invasions. Biol Invas 14(4):827–838. https://doi.org/10.1007/s10530-011-0119-3
31. Lee I-Y, Kim S-H, Lee Y-H, Hong S-H (2023) Occurrence characteristics and management plans of an ecosystem-disturbing plant, *Hypochaeris radicata*. Korean J Environ Biol 41(3):273–282. https://doi.org/10.11626/KJEB.2023.41.3.273
32. Lee SR, Choi TY, Son DC (2024) Multiple introductions of divergent lineages and admixture conferred the high invasiveness in a widespread weed *(Hypochaeris radicata*). Evol Appl 17(6):e13740. https://doi.org/10.1111/eva.13740
33. Manning CD, Raghavan P, Schütze H (2008) Introduction to information retrieval. Cambridge University Press. https://doi.org/10.1017/CBO9780511809071
34. Mehta SV, Haight RG, Homans FR, Polasky S, Venette RC (2007) Optimal detection and control strategies for invasive species management. Ecol Econ 61(2–3):237–245. https://doi.org/10.1016/j.ecolecon.2006.10.024
35. Ministry of Climate, Energy and Environment [MCEE] (2025) Act on the conservation and use of biological diversity (Act No. 21065, effective 1 October 2025). Ministry of the Environment, Sejong, Republic of Korea [ME]. (2009). *Enforcement Rule of the Wildlife Protection Act* (Ministerial Ordinance No. 332, effective 1 June 2009). Sejong, Republic of Korea
36. Ministry of the Environment (n.d.). *Environmental Geographic Information Service*. Accessed December 25, 2025. https://egis.me.go.kr/
37. Mitchell RM, Bakker JD (2014) Intraspecific trait variation driven by plasticity and ontogeny in *Hypochaeris radicata*. PLoS ONE 9(10). https://doi.org/10.1371/journal.pone.0109870. Article e109870
38. Mix C, Arens PFP, Rengelink R, Smulders MJM, Van Groenendael JM, Ouborg NJ (2006) Regional gene flow and population structure of the wind-dispersed plant species Hypochaeris radicata (Asteraceae) in an agricultural landscape. Mol Ecol 15(7):1749–1758. https://doi.org/10.1111/j.1365-294X.2006.02887.x
39. Moon TH (2015) The evolution of natural environmental preservation policies in Korea and future tasks: 1960–2013. J Environ Policy 23(2):57–95. https://doi.org/10.15301/jepa.2015.23.2.57
40. Nasa JPL (2013) NASA Shuttle Radar Topography Mission Global 1 arc second V003, Dataset NASA EOSDIS land processes DAAC. https://doi.org/10.5067/MEaSUREs/SRTM/SRTMGL1.003
41. National Institute of Ecology (n.d.). EcoBank. Accessed December 23 (2025) https://www.nie-ecobank.kr/
42. Ng K, Driscoll DA (2015) Detectability of the global weed Hypochaeris radicata is influenced by species, environment and observer characteristics. J Plant Ecol 8(4):449–455. https://doi.org/10.1093/jpe/rtu032
43. Ni M (2023) Herbarium records reveal multiple phases in the relationship between minimum residence time and invasion ranges of alien plant species. Plants People Planet 5(1):47–57. https://doi.org/10.1002/ppp3.10327

44. Ortiz MÁ, Tremetsberger K, Terrab A, Stuessy TF, García-Castaño JL, Urtubey E, Baeza CM, Ruas CF, Gibbs PE, Talavera S (2008) Phylogeography of the invasive weed *Hypochaeris radicata* (Asteraceae): From Moroccan origin to worldwide introduced populations. Mol Ecol 17(16):3654–3667. https://doi.org/10.1111/j.1365-294X.2008.03835.x
45. Osawa T, Akasaka M, Kachi N (2019) Facilitation of management plan development via spatial classification of areas invaded by alien invasive plant. Biol Invas 21(6):2067–2080. https://doi.org/10.1007/s10530-019-01958-2
46. Pedersen TL (2025) ggraph: An implementation of grammar of graphics for graphs and networks, version 2.2.2.9000, Computer software. https://ggraph.data-imaginist.com
47. Piria M, Copp G, Dick J, Duplić A, Groom Q, Jelić D, Lucy F, Roy H, Sarat E, Simonović P, Tomljanović T, Tricarico E, Weinlander M, Adámek Z (2017) Tackling invasive alien species in Europe II: Threats and opportunities until 2020. Manag Biol Invas 8(3):273–286. https://doi.org/10.3391/mbi.2017.8.3.02
48. QGIS Development Team (2025) QGIS geographic information system, version 3.22.9, Computer software. QGIS Association. https://www.qgis.org
49. R Core Team (2025) R: A language and environment for statistical computing, version 4.4.1, Computer software. R Foundation for Statistical Computing. https://www.R-project.org/
50. Ridley HN (1930) The dispersal of plants throughout the world. L. Reeve & Co
51. Ryu TB, Kim MJ, Lee CW, Kim DK, Choi DH, Lee H, Jeong HR, Lee DH, Kim NY (2017) Distribution characteristic of invasive alien plants in Jeju Island. J Ecol Environ 41(1):24. https://doi.org/10.1186/s41610-017-0042-3
52. Sharp RL, Larson LR, Green GT (2011) Factors influencing public preferences for invasive alien species management. Biol Conserv 144(8):2097–2104. https://doi.org/10.1016/j.biocon.2011.04.032
53. Silge J, Robinson D (2016) tidytext: Text mining and analysis using tidy data principles in R. J Open Source Softw 1(3):37. https://doi.org/10.21105/joss.00037
54. Simberloff D, Martin JL, Genovesi P, Maris V, Wardle DA, Aronson J, Courchamp F, Galil B, García-Berthou E, Pascal M, Pyšek P, Sousa R, Tabacchi E, Vilà M (2013) Impacts of biological invasions: What's what and the way forward. Trends Ecol Evol 28(1):58–66. https://doi.org/10.1016/j.tree.2012.07.013
55. Simberloff D, Parker IM, Windle PN (2005) Introduced species policy, management, and future research needs. Front Ecol Environ 3(1):12–20. https://doi.org/10.1890/1540-9295(2005)003[0012:ISPMAF]2.0.CO;2
56. Son D, Waldman B, Song U (2023) Effects of land-use types and the exotic species, Hypochaeris radicata, on plant diversity in human-transformed landscapes of the biosphere reserve, Jeju Island, Korea. Plant Divers 45(6):685–693. https://doi.org/10.1016/j.pld.2023.01.002
57. Soons MB, Heil GW, Nathan R, Katul GG (2004) Determinants of long-distance seed dispersal by wind in grasslands. Ecology 85(11):3056–3068. https://doi.org/10.1890/03-0522

58. Tasker AV (2011) Length of lag phase and additional factors related to introduction and early spread of invasive plants: A regulator's view. In: Leslie AR, Westbrooks RG (eds), Invasive plant management issues and challenges in the United States: 2011 overview, vol 1073. *American Chemical Society*. https://doi.org/10.1021/bk-2011-1073.ch021
59. Turkington R, Aarssen LW (1983) Biological flora of the British Isles. 156. *Hypochoeris radicata* L. (*Achyrophorus radicatus* (L.) Scop.). J Ecol 71(3):999–1022. https://doi.org/10.2307/2259604
60. Ward SF, Fei S, Liebhold AM (2020) Temporal dynamics and drivers of landscape-level spread by emerald ash borer. J Appl Ecol 57(6):1020–1030. https://doi.org/10.1111/1365-2664.13613
61. Yun KS, Shin YH (2015) The appropriateness and improvement for grade evaluation system of geomorphology part, the 3rd natural environment survey. J Korean Geomorphol Assoc 22(1):89–107. https://doi.org/10.16968/JKGA.22.1.8

Figures

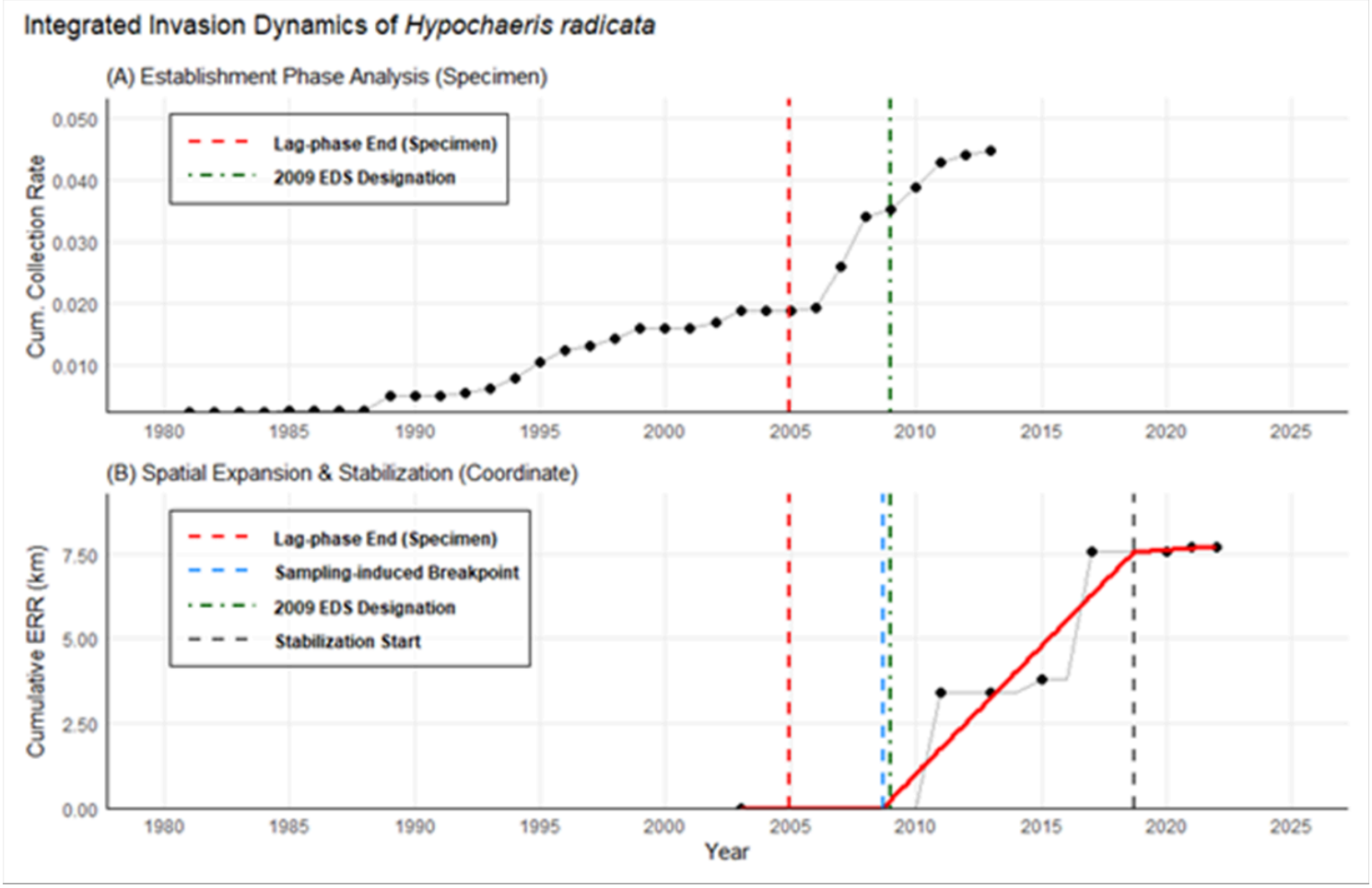

Figure 1

Integrated invasion dynamics of *Hypochaeris radicata* on the Jeju Island. (A) Establishment phase analysis based on the cumulative collection rate of herbarium specimens. The red dashed line indicates the estimated biological lag-phase end (2006.6), marking the transition from initial establishment to

temporal expansion. (B) Spatial expansion and stabilization dynamics quantified by Equivalent Radius of Range (ERR) derived from occurrence coordinates. Blue dashed line marks the sampling-induced breakpoint (2008.7) following the resumption of intensive surveys, while black dashed line indicates onset of the stabilization phase (2018.7). In both panels, green dot-dash line represents the 2009 formal legal designation of the species as an Ecosystem Disturbing Species (EDS). Red solid line in panel (B) illustrates multi-phased invasion trajectory estimated via segmented regression analysis.

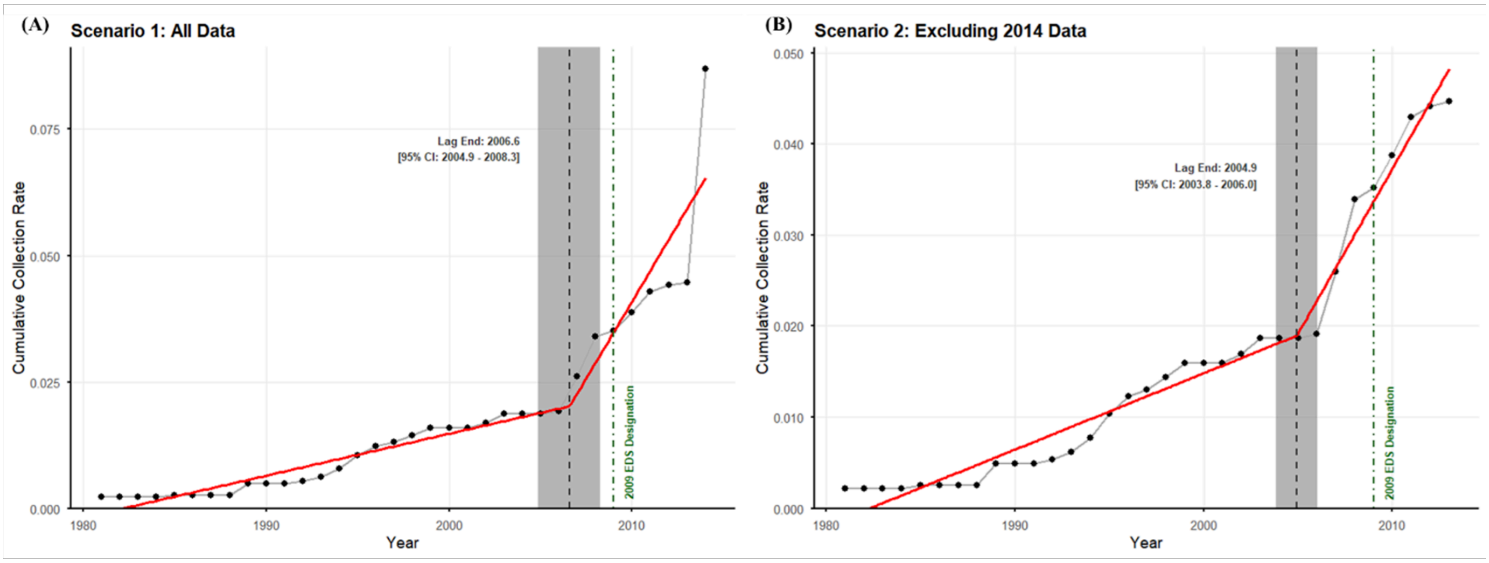

Figure 2

Sensitivity analysis of the biological lag phase for *H. radicata* establishment. Robustness of the temporal lag phase was evaluated via segmented regression under two scenarios: (A) Scenario 1 (all data), with a breakpoint at 2006.6 (95% confidence interval (CI): 2004.9–2008.3); 2014 is identified as a sampling artifact (total effort (N_{effort}) = 166). (B) Scenario 2 (excluding 2014 outlier), where lag-phase termination shifted to 2004.9 (95% CI: 2003.8–2006.0). Red solid lines represent piecewise linear fits; vertical dashed lines and shaded areas denote estimated breakpoints and 95% CIs, respectively. The green dot-dash line indicates the 2009 Ecosystem Disturbing Species (EDS) designation. Overlapping CIs confirm the stability of identified dynamics despite sampling fluctuations.

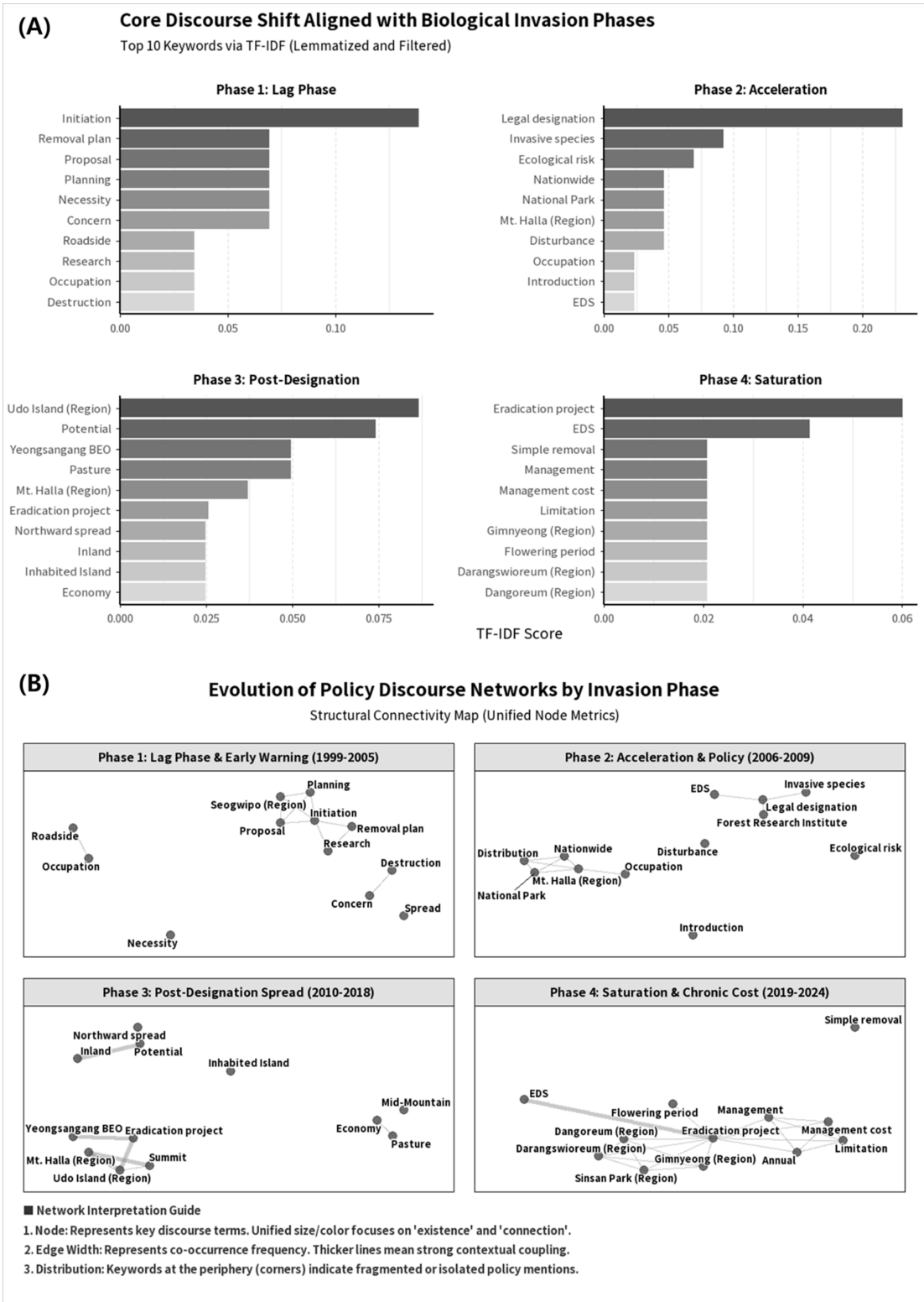

Figure 3

Spatiotemporal evolution and structural connectivity of policy discourse regarding *H. radicata*. (A) Top 10 phase-specific keywords by Term Frequency–Inverse Document Frequency (TF–IDF). A rank-based (1^{st}–10^{th}) grayscale gradient is applied for visual consistency across varying score ranges, with all terms standardized into English nomenclature. (B) Semantic network analysis (SNA)-based structural connectivity maps. Node metrics are unified to emphasize term distribution, while edge width represents

co-occurrence frequency. Kamada–Kawai layout incorporates optimized label repulsion and retains isolated nodes to visualize policy fragmentation.

Supplementary Files

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- SupplementaryInformation.docx