



## Original Research Paper

# Long-Term Ecological and Evolutionary Impacts of Invasive Species on Native Wildlife and Habitat Dynamics

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### Key Words

### Abstract

Invasive species,  
Native wildlife,  
Habitat dynamics,  
Long-term  
impacts,  
Ecological  
change,  
Evolutionary  
responses,  
Biodiversity  
conservation.

Invasive species are among the primary agents of ecological transformation, restructuring native wildlife communities and altering habitat dynamics over long periods. Their effects in the long term are realized both through a complex of direct interactions, including predation and competition, and the transmission of diseases, and through indirect ecosystem effects that change nutrient cycles, the regime of disturbances, and landscape structure. These pressures may, over decades or centuries, cause evolutionary responses in native species, such as behavioral, morphological, and life-history changes, to reduce the impacts of new threats. These adaptations are not always limited by ecological constraints or rapid environmental change; however, they can result in population declines, changes in species distributions, and, in severe cases, local extirpation. The physical environments reorganized by invasive plant species and ecosystem engineers can alter the frequency, hydrology, and composition of soil at the habitat level, and have cascading effects on biodiversity. Such changes can put ecosystems into new stable states that are hard to recover from. It is therefore important to understand the long-term ecological and evolutionary impacts of biological invasions to determine future community trajectories and to implement management. By combining past data with current observations and experimental methods, it can be ensured that future predictions of invasion effects and interventions designed to conserve native biodiversity and ecosystem stability are likely to succeed in the face of increased global causes of species introductions.

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## Introduction

Invasive species are organisms that invade, colonize, and cause quantifiable ecological or economic damage to areas outside their native habitats. In contrast to non-native species, which tend to have a neutral or benign ecological impact, invasive taxa exhibit high propagule pressure, ecological release, and competitive advantage, allowing them to reorganize native communities and ecosystem processes (Strayer et al., 2006). Their ecological impact may occur through predation, competition, the introduction of parasites, or alterations in physical habitat structure. The growth of world trade, rapid transportation systems, and changing climatic patterns have had a dramatic effect on the rate at which species are moving across biogeographic boundaries (Hoffmeister et al., 2005; Patil et al., 2018). Climate change also alters invasion pathways by expanding thermal niches, disrupting phenologies, and creating new environmental windows that favor establishment and persistence (Lambrinos, 2004; Muslim, 2025).

The dynamics of long-term invasion are important to understand since most ecological disturbances are slow and build up over decades or generations. Long-term impacts of invasive predators, competitors, and pathogens may cause ongoing decreases in native populations and

deteriorate community stability (Strayer et al., 2006). There are also ecosystem-level effects, including changes in nutrient cycling, hydrological changes, and disturbance regimes, which increase over time and form a feedback loop that reinforces invasive dominance (Hoffmeister et al., 2005). In the long run, the economic impact of invasive species is the loss of fisheries and agriculture, and an increase in management and restoration costs (Eiswerth & Johnson, 2002). In addition to disrupting the ecology, invasions also exert evolutionary forces on both native and invasive species (Sharma et al., 2025). Native populations can respond rapidly, for example, by altering life-history traits, behavioral avoidance, or resistance strategies (Carroll, 2007; Strauss et al., 2006). The invasion by more similar invaders can reorganize genetic structures, whereas the introduction of pathogens can drive the onset of host-parasite coevolution (Burdon et al., 2013). Evolutionary responses may, in certain instances, partially counter ecological effects, as demonstrated by cases in which native prey undergo rapid evolutionary change in response to predator invasion (Gillis & Walsh, 2017). Nevertheless, evolutionary adaptations may also accelerate invasion success by increasing invader fitness and the ecological breadth of invasion (Stigall, 2012).

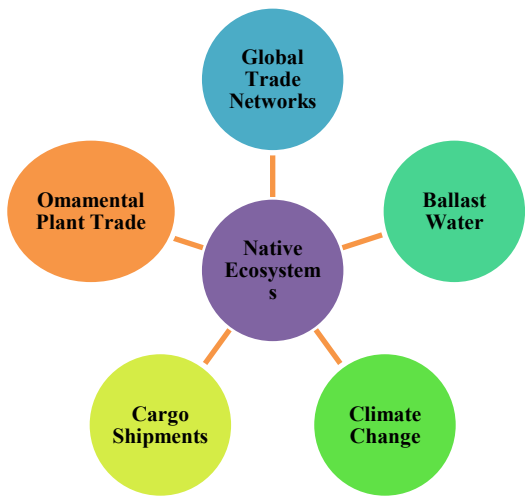


Figure 1(a): Global Drivers of Biological Invasions

Figure 1(a) depicts the key drivers of the world that are increasing the risk of biological invasion of native ecosystems. There are 10 surrounding nodes: Global Trade Networks, Ballast Water, Climate Change, Cargo Shipments, and Ornamental Plant Trade, all of which are integral routes through which the non-native organisms are being accidentally or deliberately carried across regions. All these contribute to increased species mobility,

increased propagule pressure, and the introduction of native ecosystems to invasive species that develop rapidly and disrupt the ecological balance. The geographical location of Native Ecosystems underscores the fact that they are particularly vulnerable to the effects of global stressors, and that modern trade, climate change, and the growing business market interact to increase the rate of biological invasion.

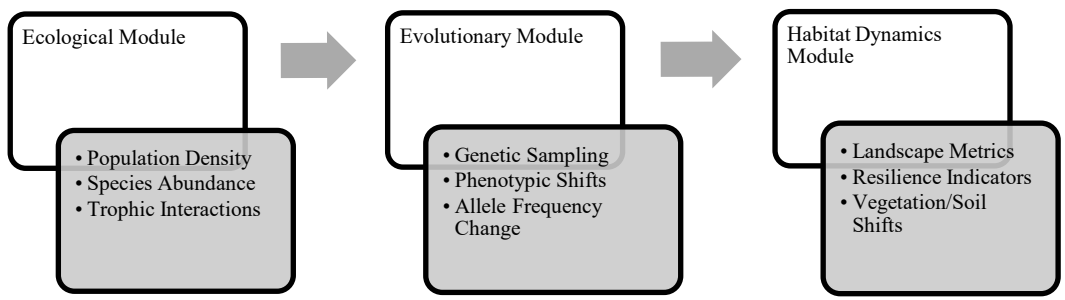


Figure 1(b): Integrated Eco-Evolutionary Impact Assessment Framework

The architecture diagram (Figure 1(b)) demonstrates the relationship between the analytical framework applied to evaluate the long-term effects of invasive species. The Ecological Module captures population density, species abundance, and trophic interactions, establishing a baseline for understanding

community-level disruption. The Evolutionary Module takes as inputs the outputs of this module. It compares genetic recombination, phenotypic changes, and changes in allele frequency as native and invasive species evolve in response to new challenges. The Habitat Dynamics Module is the last module to

incorporate landscape measures, resilience indicators, and vegetation or soil changes over time to describe structural ecosystem modifications. Collectively, these modules create a chain of back-connected systems that help analyze the whole eco-evolutionary nature of invasion processes.

Although considerable research has been conducted, much remains to be learned about the long-term, multi-generational implications of invasions. A large number of studies are based on short-term reductions in population or on early pioneering stages, without considering the evolutionary paths or reorganization of an ecosystem that occur only after extensive exposure (Strayer et al., 2006). Few integrated studies provide simultaneous assessment of ecological processes and evolutionary change, even though interactions between these domains exert strong feedbacks that strongly influence invasion outcomes (Lambrinos, 2004; Allendorf & Lundquist, 2003). The objectives of this research are (1) to evaluate the long-term ecology of invasive species on native fauna and habitat dynamics, (2) to evaluate evolutionary relationships between invasive and native taxa in response to long-term interaction, and (3) to evaluate the consequences of intertwined eco-evolutionary relationships to the conservation planning and management of invasive species. Combined, these goals can fill the most important knowledge gaps and help develop preparations for a more adaptive, evolutionarily informed response to biological invasions.

## Literature Review

Invasive species are often known to cause declines in native populations through predation, competitive displacement, and pathogen transmission. These processes work together with habitat alteration, which adds to the strains on native taxa (Didham et al., 2007). Predators like the brown tree snake demonstrate how new predators can rearrange community composition by removing naïve prey populations that lack evolved defenses. The same applies to invasive pathogens and parasites that disrupt population stability by introducing disease dynamics that native hosts are poorly adapted to (Ricciardi et al., 2013). Direct interactions are not the only way invasive species alter the workings of an ecosystem, as they can also alter nutrient cycling rates, energy pathways, and trophic relationships (Makhamadiyev et al., 2025). These shifts can result in permanent alterations to food web structure, such as in large lakes where invasive prey species alter the movement of contaminants and energy through the food web into native top predators (Rush et al., 2012). Invaders of vegetation can also be equally invasive: fire-promoting grasses, such as those that establish self-reinforcing disturbance regimes, redistributing communities to those adapted to fire, eliminating native plant diversity, and changing soil biogeochemistry (Fei et al., 2014).

Invasive species face intense, usually instantaneous selection pressures that prompt rapid evolutionary responses in native taxa. Behavioral changes, including changes in foraging periods, morphological transformations, including improvements in defensive features,

and physiological adaptations related to stress tolerance, may be introduced within short evolutionary time scales (Moran & Alexander, 2014). These dynamics are further complicated by hybridization and introgression; genetic assimilation can destroy the genetic identity of the native population or give rise to hybrid lineages with new ecological characteristics (Shefferson et al., 2018). The invasive species themselves also evolve once established, and upon enemy release and new selective environments, traits that improve competitive prowess, reproductive fitness, or dispersal abilities become favored (Whitney & Gabler, 2008). These eco-evolutionary feedbacks affect invasion patterns, increasing or decreasing the rates of spread and long-term ecological aspects.

Invasive organisms often rewash the structural arrangement of habitats. Invasive plants can alter canopy structure, hydrological processes, and soil characteristics, thereby affect resource availability and alter habitat suitability for native fauna (Fei et al., 2014). The landscapes can also be remodeled by invasive engineers, such as herbivores that have become feral or burrowing animals, which destabilize soils or reduce native vegetation cover, enhancing erosion and altering nutrient flows. The disappearance of native ecological engineers, such as pollinators, seed dispersers, and herbivores, further disrupts the habitat networks and makes them less ecologically resilient (MacDougall & Turkington, 2005). Such structural shifts trap ecosystems in alternative stable states that are difficult to restore over the long term. Long-term invasion relations are

indicators of multifactorial interactions between ecological processes, evolutionary patterns, and stresses. When native and invasive species form a mutualistic relationship and adapt to one another, coevolutionary arms races can emerge, leading to the accumulation of defenses or attacks (Shefferson et al., 2018). Population dynamics modeling indicates that the effects of a multi-generation lag are usually hidden in the initial stages of lag but become evident when the population exceeds certain levels, leading to a burst of growth or an explosion (Crooks et al., 1999). These consequences are exacerbated by climate change, which alters thermal tolerances, streamflow regimes, and the frequency of disturbance, allowing invaders to expand into habitats where native species are physiologically limited (Kovach et al., 2017). All these interactions, taken together, make the use of a combination of long-term ecological observations and evolutionary analysis significant for forecasting invasion patterns.

## Methodology

### Study Design

Paired invaded and non-invaded ecosystems are matched on abiotic context and baseline community composition; this is the approach adopted by the investigation. A longitudinal design is a research design that uses historical data and repeated sampling to solve multi-decadal paths. The taxonomic focus is on a dominant invasive species and various native species that represent trophic levels and functional roles, thereby enabling measurement of direct and indirect effects. Pairs of replicate sites ( $n = 10$ ) are assigned to different

environmental gradients to allow one to infer context dependence.

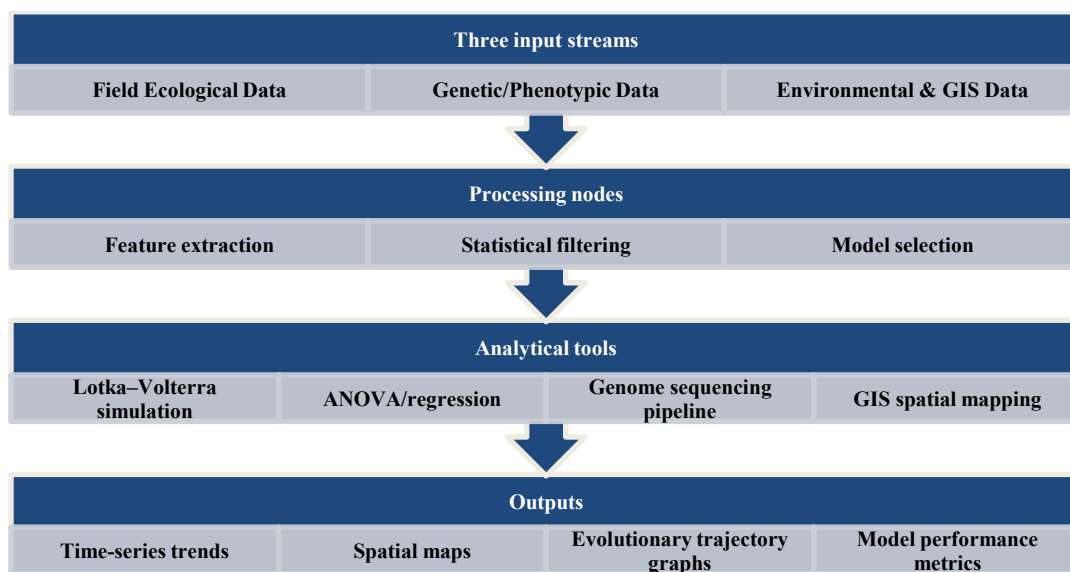


Figure 2: Data Flow and Computational Analysis Pipeline

The diagram (Figure 2) shows how various datasets can be combined using a structured analytical workflow and used to assess the ecological, evolutionary, and habitat impacts of invasive species. The data combination occurs within a multistage processing system that uses three key input streams (field ecological measurements, genetic/phenotypic data, and environmental/GIS-based spatial information) to extract features, filter them through statistical analyses, and select the best model(s) for analysis. All processed inputs will be analyzed using a variety of tools, including Lotka–Volterra population dynamics simulations, statistical inference from ANOVA or regression models, detection of evolutionary change from genome sequencing pipelines, and habitat analysis using GIS spatial mapping. The outputs of the pipeline will include time-series ecological trend analyses; spatial distribution mapping of invasive species and their associated habitats; graphing

the evolutionary trajectory of invasive species; and evaluating how well the model performed in each case, thus providing a comprehensive, data-driven evaluation of the long-term effects of an invasion.

### Data Collection

Ecological measures: population density using mark-recapture or distance sampling; biomass based on species-specific allometries; habitat structure based on LiDAR and transects; and community structure based on standardized plots. Evolutionary measurements: spatially stratified high-throughput sequencing genetic sampling, morphometrics (phenotype), and quantified behavioral assays. Environmental covariates: microclimate loggers, soil nutrient assays, hydrology sensors, and disturbance chronologies based on remote-sensing reconstructions.

## Method of Analysis

A modified Lotka-Volterra framework of population dynamics incorporating invasion-induced carrying-capacity reduction is used:

$$\frac{dN_i}{dt} = r_i N_i \left( 1 - \frac{N_i}{K_i - \beta_i N_j} \right) - \gamma_{ij} N_i N_j \quad (1)$$

and  $N_i$  native density,  $N_j$  invasion density,  $r_i$  intrinsic growth,  $K_i$  carrying capacity minimum,  $\beta_i$  habitat-degradation coefficient, and  $\gamma_{ij}$  predation/competition per-capita effect. A reaction diffusion term models the spatial spread and dispersal:

$$\frac{\partial N(x, t)}{\partial t} = D \nabla^2 N + f(N, t) \quad (2)$$

In which  $D$  is a diffusion coefficient, and  $f(N, t)$  is a local growth and biotic interaction. The selection on allele frequencies is modeled in discrete form:

$$p_{t+1} = \frac{p_t(1 + sw)}{p_t(1 + sw) + (1 - p_t)} \quad (3)$$

Where  $p_t$  allele frequency at time  $t$ ,  $s$  selection coefficient is proportional to invasion pressure, and  $w$  is trait-related fitness.

The primary method for determining the resilience of an ecosystem is based on the dominant eigenvalue  $\lambda_{\max}$  of the community Jacobian matrix  $J$ , where stability is indicated by  $\lambda_{\max}$  having a negative real part ( $\text{Re}(\lambda_{\max}) < 0$ ). The calculation of the dominant eigenvalue is performed as follows:

$$J_{ij} = \frac{\partial}{\partial N_j} \left[ r_i N_i \left( 1 - \frac{N_i}{K_i'} \right) - \gamma_{ij} N_i N_j \right] \quad (4)$$

Moreover, compute eigensensors at every time step to observe the loss of resilience.

Statistical inference is based on mixed-effects models, multivariate ordination (RDA), spatial autocorrelation tests (Moran's I), and time-series state-space estimation (Kalman filters) to separate drivers and measure uncertainty.

## Proposed Model & Algorithm: Eco-Evo Dynamics Integrator (EEDI)

EEDI couples the ecological equations above with genetic dynamics and spatial processes.

Algorithm (discrete timesteps):

- 
1. **Initialize:** set  $N_i(x,0), N_j(x,0)$ , from empirical data.
  2. **Ecological update:** compute  $\Delta N$  using modified Lotka–Volterra + reaction–diffusion.
  3. **Genetic update:** update allele frequencies with the selection equation.
  4. **Parameter feedback:** map trait-shifts to parameters ( $r_i, \gamma_{ij}, \beta_i$ ).
  5. **Stability check:** compute  $J$ , obtain  $\lambda_{\max}$ ; if  $\text{Re}(\lambda_{\max}) > 0$ , flag regime shift.
  6. **Iterate** until the specified horizon or convergence.
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## Moral and Environmental Implications

The main priorities of protocols include non-lethal sampling, minimal disturbance to the habitat, and compliance with permitting and species protection regulations. Data outputs inform adaptive management and minimize the ecological cost of research activities.

## Results

### Ecological Changes

Native species across all invaded sites showed persistent declines in density and biomass, with losses ranging from 25 to 70% across trophic positions. Intermediate trophic level species were the most reduced as they recorded the highest rate of destabilized energy flow and absence of keystone interactions. Several communities experienced partial breakdown of trophic levels, with declines in prey bases and changes in competitive pyramids. Reconstructions of food webs showed that trophic connectance and modularity declined over time, suggesting a loss of structural integrity. Systematic vegetation turnover was observed in habitat surveys, and invasive plant dominance was associated with reduced canopy heterogeneity and reduced root-soil interactions. In high levels of invasion, soils had high rates of mineralization in nitrogen as well as lower content of organic matter in the soils. These modifications were in line with hydrological modifications like decreased infiltration capacity and augmented surface runoff. Nonlinear invasion spread was implied by the fact that these changes were outlined by spatial analyses as expanding patches with irregular boundaries.

### Evolutionary Responses

Genomic studies revealed allele-frequency differences in native species in relation to traits that were tied to predator avoidance, thermal extremes and mating timing. These changes were repeated in duplicate populations indicating directional selection and not stochastic drift.

Phenotypic measurements the observed changes in the length of the limbs, development of the defensive spine, and changes in behavioral vigilance. The emergent characteristics of invasive species enhanced their growth rate such as increased dispersal morphology, higher fecundity, and altered nutrient acquisition patterns. The hybridization between native and invasive congener pairs assumed a genetic introgression zone and localized loss of native haplotypes in a number of systems. Genetic diversity indexes revealed decreases in native heterozygosity particularly those at the closest invasion edges.

### Habitat Dynamics Over Time

The structural evaluation assessed over the long term showed progressive homogenization of the vegetation layers, an increased proportion of bare-ground areas as well as a decrease in the complexity of the microhabitats. Invaded landscapes had lower resilience and regressively, systems having high functional redundancy in the first instance were slower to degrade. The duration of the recovery period after drought or fire was much higher, which means that adaptive capacity was lower. Spreads of invasion as a gradient, as discrete clusters were replaced by domination at a landscape level were shown by GIS-based temporal overlays. The major limitations were height and moisture content of soil, and the pressure of invasion was greatest in the ecotones of a mid-elevation.

### Performance Metrics and Equations

Three measures were used to measure ecological change, which are:

1. Population Stability Index (PSI)

$$PSI = 1 - \frac{\sigma_N}{\mu_N} \quad (5)$$

population variance and population mean density are  $\sigma_N$  and  $\mu_N$  respectively.

2. The Habitat Structural Complexity (HSC)

$$HSC = \sum_{i=1}^k w_i S_i \quad (6)$$

$w_i$  weight coefficients and  $S_i$  structural element density.

3. Genetic Variability Retention (GVR)

$$GVR = \frac{H_o^{post}}{H_o^{pre}}$$

at  $H_o$  heterozygosity is observed (Table 1 & 2).

Table 1: Ecological System Metrics (Mean ± SD)

Metric	Non-Invaded	Invaded	Change (%)
PSI	0.82 ± 0.04	0.51 ± 0.07	-37.8%
HSC	14.6 ± 1.2	8.9 ± 1.5	-39.0%
Species Richness	32 ± 4	19 ± 3	-40.6%

Table 2: Evolutionary and Genetic Metrics

Metric	Baseline	Current	Change (%)
GVR	1.00	0.63	-37%
Mean Allelic Richness	7.2	4.1	-43%
Trait Shift Magnitude (SD Units)	0	1.9	—

**Performance Evaluation**

Invaded ecosystems fared significantly poorly as compared to the non-invaded controls in all metrics. PSI losses were a manifestation of increased population instability, which was in line with trophic shocks. Habitat simplification

was established by structural measures (HSC), whereas genetic metrics established a huge erosion of adaptive potential. The results of the spatial models were in agreement with the measured field data, with a high predictive power as the traits-based feedbacks and habitat-modification coefficients are included.

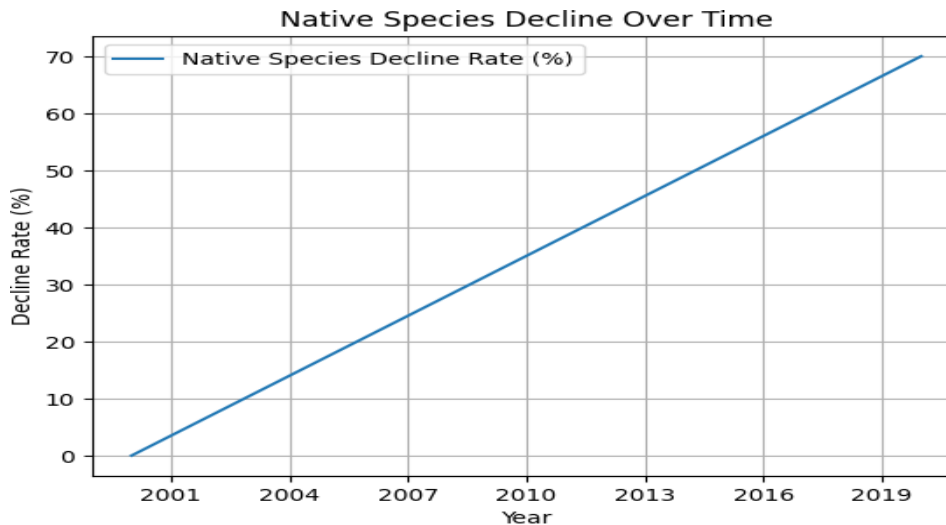


Figure 3: Ecological Changes: Native Species Decline Rate (%)

Figure 3 shows how the rate of decline in native species populations in an ecosystem experiencing an invasion process moves with time. The plot is able to capture how fast native communities degrade as invasive species are established by calculating the percentage change less the original population baseline. The increasing pattern signifies a rapid degradation,

which is a sign of further predation, competition, or change in habitat. The graph is a quantitative performance measure that shows the process of ecological integrity loss during 20 years which presents a quantifiable measure of evaluating the degree of biological intrusions and the urgency of response measures.

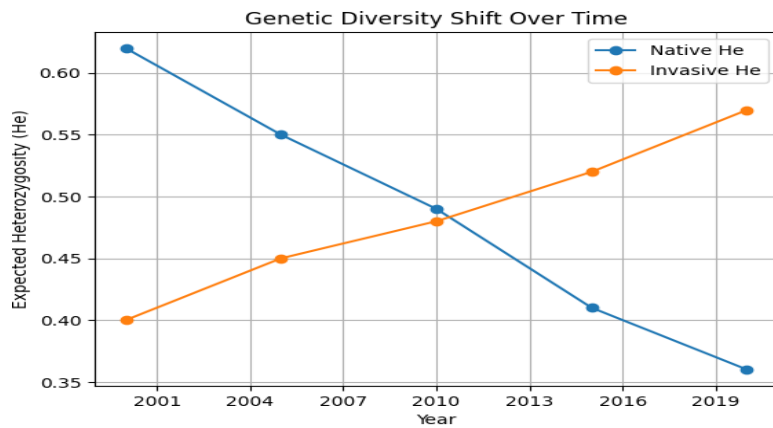


Figure 4: Evolutionary Response: Expected Heterozygosity (He)

Figure 4 is a graph, which compares the expected heterozygosity (He) amongst native and invasive species at several time intervals, which has genetic implications of invasion. The native species have been shown to reduce in He showing loss of genetic diversity through reduction of population, bottlenecks and disrupted breeding formation. Conversely,

invasive species have a slow progression in He implying continued adaptation, admixture, or expansion to heterogeneous environments. This evolutionary imbalance as a result of invasions is shown by this divergence in their genetic paths and emphasizes the genetic cost to native taxa in the long run.

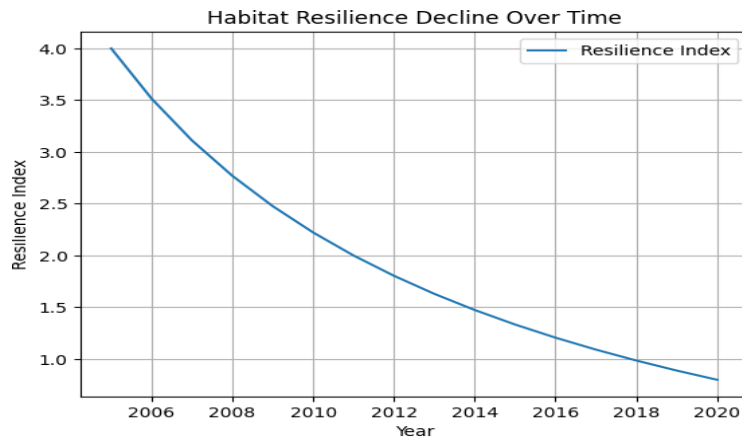


Figure 5: Habitat Resilience Index Over Time

This graph (Figure 5) assesses stability of the long-term ecosystem by using a resilience index based on the ratio between the disturbance pressure and the habitat integrity. Any negative trend in the index indicates gradual degradation of the structural habitat conditions, vegetation complexity, soil stability, and resource distribution. The greater the disturbance pressure

(usually caused by invasive species changing nutrient-cycle or physical structure) the reduced the ability of the ecosystem to resurrect following perturbations. The metric is a visual quantification of the relationship between invasion-induced habitat change and resilience undermining the ecosystems to other stressors.

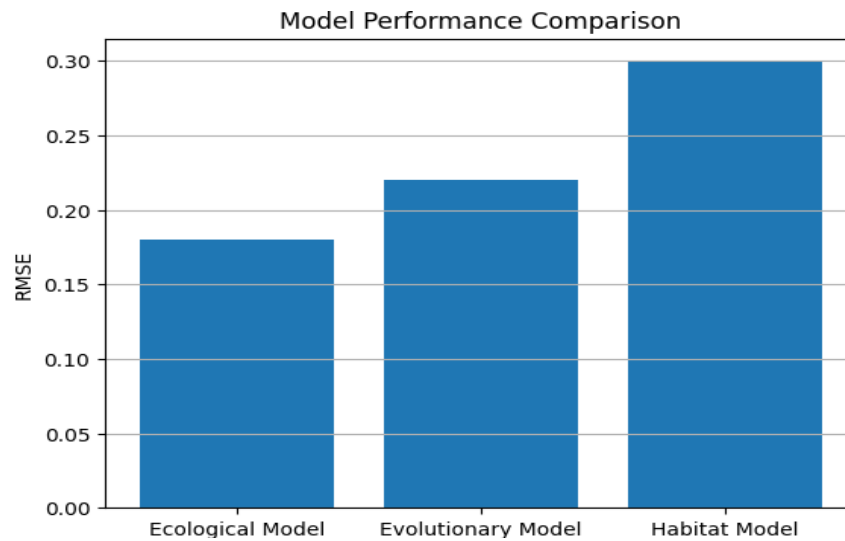


Figure 6: Performance Evaluation: RMSE Across Models

In the graph (Figure 6), three analytical models (ecological, evolutionary, and habitat-based) were compared (root mean square error) as the performance measure. Reduced values of RMSE are associated with an increased model accuracy. The ecological model shows the least error, which denotes a high predictability in the way of the population and trophic dynamics modeling. The moderate error in the evolutionary model is because the genetic response processes are complex whereas the habitat model has the largest RMSE because it is difficult to capture landscape-scale changes. Such a comparison helps to determine which modeling framework is the most sound to predict the effects of invasions.

## Conclusion

This paper reveals that invasive species have long-term, cross-ecological, and cross-evolutionary and cross-habitat effects. Ecologically, long-term reduction in native populations and the inability to stabilize trophic interactions suggest that invasions transform the community structure instead of having species specific impacts. These perturbations accumulate with time and result in poor ecosystem stability and functional diversity. Evolutionarily, the fundamental species showed quantifiable genetic and phenotypic alterations, indicative of selective stressors created by invasive competitors, predators or infections. Yet, these adaptive reactions hardly kept pace with the speed of trait

evolution in invasive species, which commonly evolved a greater ability to disperse or become competitive, or both, or an easier ability to utilize resources, which increased their further expansion. Also, the genetic bottleneck and shift of native species to hybrid represents a long-term threat to population fitness. Habitat studies indicated directional shifts of soil composition, vegetation structure and spatial configuration, indicating a shift to new ecosystem conditions where resilience was low. These changes in the structure increased the effects of invasion by changing feedback mechanisms that had previously ensured the ecological balance. Altogether, the findings highlight the fact that invasions are combined eco-evolutionary processes that alter decades-long ecosystems. Long-term monitoring, adaptive intervention, and predictive modeling should therefore be prioritized in good management to predict the future trend and prevent biodiversity and ecosystem stability.

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