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Review Article

Plant Invasive Species Success Strategies and Their Impact on Ecosystems

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ABSTRACT

Another ecological theory relates to the concept of limiting similarity. This theory proposes that invasive species have characteristics that are different from those of native species within an ecosystem. Research has shown that invasive species have wider physiological niches, more efficient means of acquiring resources, and traits associated with the fast-return end of the leaf economics spectrum (LES). Invasive species have lower leaf mass per square meter, higher rates of carbon assimilation, and higher nitrogen content in their leaves. These characteristics enable invasive species to thrive in resource-poor environments. Also, invasive species exhibit high phenotypic plasticity, enabling them to survive in diverse environmental conditions. Such plasticity is associated with features such as the ability of invasive species to develop their leaves early in their life cycle, high water-use efficiency, and high photosynthesis rates at low light intensities. Such traits provide invasive species with a competitive advantage over native species. Overall, the complexity of invasive plant species is well documented in the scientific literature. While many factors contribute to the success of invasive species, including resource availability, disturbance regimes, and environmental changes, it is necessary to study their physiological traits to develop management strategies. So, continued research into the invasiveness of plant species, especially in resource-poor environments, is needed to understand the mechanisms behind their invasiveness and to develop effective management plans to control their impact on ecosystems.

1. Introduction

In many parts of the world, specific non-native flora causes significant ecological disruption. The non-native species exhibits growth rates significantly higher than those of the native flora in those areas, allowing for more rapid spread; it has mechanisms to protect itself from other species in those environments; and it can inhibit the growth of other plant species there. *Pueraria montana* (Kudzu), for instance, forms dense canopies that prevent most other native plants from receiving sunlight; *Reynoutria japonica* (Japanese knotweed) also forms dense stands that exclude all other vegetation; and *Prosopis juliflora*, in arid regions, creates vast stands of a single species that alter the soil chemistry and dry out water from below the roots. Another area that is prone to semantic ambiguity is the study of ecology. For instance, a species is considered invasive if it is introduced by humans (intentionally or otherwise) and causes environmental, economic, or human health damage (Diagne, C. et.al., 2021). While various ecological models exist, IPBES is one of the organizations that recognizes the impact of invasive alien species on biodiversity worldwide. The invasive success of species is determined by interactions with target ecosystems, which shape phenotypic traits and vulnerability to invasive species; both factors are influenced by climate change and ecosystem fragmentation driven by human activities. The introduced species exhibit features such as rapid growth, high fecundity, and high adaptability to a variety of environments.

Invasive alien plants (IAPs) fundamentally restructure ecosystem architecture and destabilize native food webs. By aggressively monopolizing light, water, and soil nutrients, these species systematically crowd out indigenous flora. When primary producer diversity collapses, the effects ripple upward: specialized insects, herbivores, and bird populations face acute nutritional deficits and critical phenological mismatches.

Biogeochemical cycles also shift under the pressure of invasions. Rapid biomass production alters soil nutrient fluxes—often through novel, nitrogen-fixing symbioses that prime the environment for secondary weeds rather than adapted native species. At the same time, dense infestations of volatile, highly flammable invasive biomass can rewrite natural fire regimes, trapping landscapes in frequent, high-intensity wildfire cycles.

The financial fallout is equally severe, driving sharp losses across agriculture, forestry, and fisheries (Keane, R. M. et.al., 2002). In farming systems, direct weed interference depresses crop yields while escalating management overhead. Similarly, in commercial forestry, aggressive IAP colonization impedes timber regeneration, forcing both the public and private sectors to bear heavy, long-term eradication costs.

These pressures extend well into public health; many invasive plants generate potent airborne allergens or create microhabitats that shelter vectors of zoonotic diseases. Countering such a multi-front threat requires integrated strategies that bridge empirical field research, environmental policy, funding models, and public health initiatives. This paper delineates these ecological impacts, economic pressures, and contemporary management frameworks.

For a structured overview, the origin, mechanisms of dominance, vulnerable regions, ecological impacts, and control strategies are presented in Table 1. Visual documentation of key invasive species discussed in this review has been provided in Figure S1 and Table S1, with image attributions.

Table 1: Origin of IPS, mechanism of dominance, dominance region, impact on local species, and control strategies

Species Name	Origin	Dominant Region(s)	Impact on Local Species & Ecosystem	Prevention & Control Strategies
Kudzu (*Pueraria montana*)	Asia	Southeastern U.S.	Smothers native vegetation by blocking sunlight; overruns forests, buildings, and infrastructure.	Mechanical removal (mowing, cutting), chemical herbicides, and targeted grazing.
Japanese Knotweed (*Reynoutria japonica*)	Asia	North America, Europe	Forms dense, sterile monocultures; can damage building foundations and infrastructure due to strong rhizomes.	Herbicides (especially stem injection), repeated cutting, and burying contaminated soil.
Giant Hogweed (*Heracleum mantegazzianum*)	Caucasus Mountains	Europe, U.S., Canada	Its sap causes severe skin burns and blisters upon contact with sunlight; displaces native plants.	Mechanical removal (digging up roots), herbicides, and public awareness campaigns.
Purple Loosestrife (*Lythrum salicaria*)	Eurasia	North America	Invades wetlands, outcompeting native plants like cattails and reducing habitat for waterfowl.	Biological control (leaf-eating beetles), mechanical removal, and herbicides.
Common Reed (*Phragmites australis*)	Eurasia	North America, worldwide	Forms dense stands that alter hydrology, crowd out native plants, and reduce biodiversity.	Controlled burning, herbicides, mechanical removal, and water level manipulation.
Garlic Mustard (*Alliaria petiolata*)	Europe	North America	Produces allelopathic chemicals that inhibit the growth of native plants and fungi; threatens forest wildflowers.	Hand-pulling, chemical treatments, and prescribed burns.
Water Hyacinth (*Eichhornia crassipes*)	South America	Tropics, subtropics (worldwide)	Forms dense mats on water surfaces, blocking sunlight, reducing oxygen, and harming aquatic life.	Mechanical removal, biological control (weevils), and herbicides.

Himalayan Balsam (*Impatiens glandulifera*)	Himalayas	Europe, New Zealand	Outcompetes native plants, attracts pollinators away from native species, and dies back in winter, leaving riverbanks vulnerable to erosion.	Hand-pulling, mowing before flowering, and targeted herbicides.
Tree of Heaven (*Ailanthus altissima*)	China	Worldwide	Produces allelopathic chemicals that poison other plants; resprouts vigorously and damages pavement and sewers.	Girdling, cut-stump herbicide application, and removing seedlings.
Privet (*Ligustrum* spp.)	Asia, Europe	U.S., Australia, worldwide	Forms dense thickets that shade out and displace native understory plants in forests.	Mechanical cutting followed by herbicide application on stumps.
Multiflora Rose (*Rosa multiflora*)	Eastern Asia	U.S.	Forms impenetrable, thorny thickets that outcompete native plants and impede wildlife movement.	Herbicides, mowing, and prescribed fire.
Saltcedar (*Tamarix* spp.)	Eurasia	Western U.S., Mexico	Draws up high levels of water, concentrates salt in the soil, and reduces water availability for native plants.	Biological control (leaf beetles), mechanical removal, and herbicides.
Spotted Knapweed (*Centaurea stoebe*)	Eurasia	U.S., Canada	Releases a root chemical that is toxic to other plants, reducing forage for livestock and wildlife.	Biocontrol (weevils), herbicides, and grazing.
Leafy Spurge (*Euphorbia esula*)	Europe, Asia	U.S., Canada	Outcompetes native grasses in rangelands, is toxic to most livestock, and is extremely difficult to eradicate due to a large root system.	Biological control (fleabeetles), chemical control, and prescribed burns.
English Ivy (*Hedera helix*)	Europe, Western Asia	U.S., Australia	Smothers ground cover, shrubs, and trees, creating a "green desert" on the forest floor.	Mechanical removal (cutting vines, pulling plants), and herbicides.
Russian Olive (*Elaeagnus angustifolia*)	Eurasia	Western U.S., Canada	Outcompetes native species for water and light, can alter soil nutrient cycling, and provides poor food and nesting for birds.	Cut-stump herbicide application and girdling.
Yellow Star Thistle (*Centaurea solstitialis*)	Eurasia	Western U.S., Australia	Creates dense, spiny infestations that injure livestock and reduce forage quality.	Biological control (weevils), grazing, and herbicides.
Dalmatian Toadflax (*Linaria dalmatica*)	Mediterranean	Western U.S., Canada	Produces a waxy coating that resists herbicides and outcompetes native grasses and forbs.	Biological control (stem weevils, root-boring weevils), and herbicides.
Water Milfoil (*Myriophyllum spicatum*)	Eurasia	North America	Forms dense mats in lakes and rivers, impeding recreation, harming fisheries, and displacing native aquatic plants.	Aquatic herbicides, mechanical harvesting, and water drawdown.
Cogongrass (*Imperata cylindrica*)	Southeast Asia	Southeastern U.S.	Forms dense, fire-prone monocultures that displace native plants and increase wildfire intensity.	Herbicides and prescribed burning to weaken the plant.

Brazilian Pepper Tree (*Schinus terebinthifolia*)	Brazil, Argentina	Florida, Hawaii, worldwide	Forms dense thickets that shade out native coastal and wetland vegetation.	Chemical control (basal bark or cut-stump), and mechanical removal.
Lantana (*Lantana camara*)	Tropical America	Worldwide	Forms dense, thorny shrubs that outcompete native plants; leaves and berries are toxic to livestock.	Mechanical removal, herbicides, and biological control (lace bugs, leafminers).
Reed Canary Grass (*Phalaris arundinacea*)	Eurasia	North America	Forms dense monocultures that reduce wetland biodiversity and alter water flow.	Mechanical removal, herbicides, and prescribed burns.
Cattail (*Typha* spp.)	Temperate Regions	Wetlands Worldwide	Forms dense, impenetrable stands that displace native wetland vegetation and reduce habitat.	Water level manipulation, cutting below the water line, and herbicides.
Canada Thistle (*Cirsium arvense*)	Europe, Asia	North America, worldwide	Spreads aggressively via rhizomes, outcompeting native species in fields and pastures.	Herbicides, mowing, and competitive planting of native species.
Queen Anne's Lace (*Daucus carota*)	Europe, Asia	Worldwide	Competes with native plants and crops for resources, especially in disturbed areas.	Herbicides and mowing before seed set.
Common Buckthorn (*Rhamnus cathartica*)	Europe, Asia	North America	Creates dense stands that shade out native species and alter soil chemistry, affecting native plant diversity.	Cut-stump herbicide application and pulling small plants.
Bohemian Knotweed (*Reynoutria × bohemica*)	Europe	North America, Europe	An aggressive hybrid of Japanese and Giant Knotweed with similar destructive properties.	Herbicide application and repeated cutting.
Alligator Weed (*Alternanthera philoxeroides*)	South America	Southern U.S., Asia, Australia	Forms dense floating mats in waterways, obstructing navigation and reducing biodiversity.	Biological control (flea beetles, stemborers), and herbicides.
Eurasian Watermilfoil (*Myriophyllum spicatum*)	Eurasia	North America	Forms dense mats that shade out other aquatic plants and interfere with recreation.	Herbicides and mechanical harvesting.
Mile-a-minute Weed (*Persicaria perfoliata*)	Asia	Eastern U.S.	Extremely fast-growing vine that smothers native plants and tree seedlings.	Mechanical removal (hand-pulling), chemical control, and biological control (weevil).
Hydrilla (*Hydrilla verticillata*)	Korea	U.S., worldwide	Forms dense underwater mats that displace native aquatic plants and clog waterways.	Herbicides, mechanical harvesting, and biological control (grass carp).
Siberian Elm (*Ulmus pumila*)	Asia	North America, worldwide	Forms dense stands that outcompete native trees and can be a host for pests.	Girdling and cut-stump herbicide treatment.

Sericea Lespedeza (*Lespedeza cuneata*)	Asia	Eastern U.S.	Forms dense stands in pastures and grasslands, reducing forage quality and biodiversity.	Herbicides and prescribed burning.
Tansy Ragwort (*Senecio jacobaea*)	Eurasia	Western U.S., Australia	Highly toxic to livestock and competes with native forage plants.	Biological control (cinnabar moth, fleabeetles) and herbicides.
Spurge Laurel (*Daphne laureola*)	Europe, North Africa	Western U.S., Canada	Creates dense stands that outcompete native understory plants, and all parts are toxic to humans and animals.	Hand-pulling and cut-stump herbicide application.
Creeping Bellflower (*Campanula rapunculoides*)	Europe, Asia	North America	Spreads aggressively via rhizomes, outcompeting native plants in gardens and wildlands.	Repeated digging to remove all root parts, and herbicides.
Periwinkle (*Vinca min*or)	Europe	North America, Australia	Forms a dense ground cover that chokes out native wildflowers and young trees.	Hand-pulling, mechanical removal, and herbicides.
	Europe, Asia	North America, Australia	Toxic to livestock and can displace native plants in rangelands.	Biological control (beetles, gall mites), and herbicides.
Bouncingbet (*Saponaria officinalis*)	Eurasia	North America	Competes with native vegetation and contains compounds that are toxic to fish.	Mechanical removal and herbicides.

2. Methodology

To evaluate the physiological and ecological drivers of plant invasions, we conducted a systematic literature review of peer-reviewed studies published between 1958 and 2024. Using Scopus, Web of Science, and Google Scholar, we searched for combinations of keywords including invasive plant species, plant invasion mechanisms, ecophysiological traits, resource acquisition, and invasive species management. We selected articles offering empirical data or theoretical insights into the functional traits, competitive strategies, and ecological impacts of invasive alien plants (IAPs).

3. Importance of understanding invasion mechanisms

Anticipating plant invasions requires moving away from reactive eradication toward predictive, proactive management. Successfully shifting this paradigm depends on decoding the specific reproductive, dispersal, and competitive traits that drive colonization.

A species' capacity to colonize new territory relies heavily on high fecundity combined with versatile dispersal vectors, such as wind (anemochory), water (hydrochory), or animal transport (epizoochory). Once established in a recipient ecosystem, these invaders frequently benefit from enemy release, facing little to no pressure from the specialized native insects or pathogens that kept their populations in check within their native range. Many invasive alien plants (IAPs) also weaponize allelopathy, secreting phytotoxic secondary metabolites into the rhizosphere to actively suppress the germination and growth of competing native species (Bais et al., 2003; Elton, 1958).

Recognizing these life-history traits is what makes targeted ecological interventions possible. For example, when dealing with species that propagate vegetatively via subterranean rhizomes or stolons, management frameworks must strictly avoid mechanical soil disturbance, which can fragment and inadvertently clone the weed. Instead, protocols must focus on the exhaustive extraction of all underground biomass. Conversely, managing ruderal invaders—which thrive in highly disturbed environments—demands immediate revegetation of cleared soils to prevent them from monopolizing resources and outcompeting opportunistic pioneers.

Integrating these traits into predictive modeling allows for far more robust risk assessments. Rather than deploying resources arbitrarily, land managers can use empirical survival thresholds and dispersal data to pinpoint high-risk zones well before naturalization occurs. This predictive foresight is becoming indispensable under shifting global climate regimes, where changing environmental baselines continually alter ecosystem vulnerability. Ultimately, these insights anchor localized restoration—by forecasting how aggressive pioneers will interact with native successional trajectories—and optimize the distribution of finite conservation funding at the policy level.

3. Historical context and evolution of invasion biology

3.1 The Eltonian Foundation (1958)

The formal tracking of non-native species introductions began at the turn of the twentieth century, laying the initial groundwork for documenting geographic shifts in flora and fauna.

The Eltonian Foundation, 1958; Charles Elton's seminal monograph, *The Ecology of Invasions by Animals and Plants*, established the foundational paradigm for modern invasion ecology. Elton explicitly identified human-disturbed and altered landscapes as the primary vectors driving the establishment and proliferation of alien species (MacArthur, R. et al., 1967).

3.2 The Shift to Colonization Traits (1970s–1980s)

The Shift to Colonization Traits, 1970s–1980s: Theoretical frameworks shifted toward defining the specific ecological traits that govern colonization success. This era formalized the enemy release hypothesis, which posits that non-native species achieve demographic dominance by escaping the specialized, co-evolved predators, herbivores, and pathogens that naturally regulate their populations in their native ranges. Concurrently, researchers began evaluating the counter-mechanisms of biotic resistance, investigating how established indigenous communities might repel invaders through intense competition for resources.

3.3 Integration with Community Assembly (1980s–1990s)

Integration with Community Assembly, 1980s–1990s; Invasion ecology became deeply integrated with community assembly theory (Simberloff, D., 2011), yielding two core concepts centered on niche saturation and competitive exclusion.

The first, limiting similarity, suggests that if an introduced species exhibits high ecomorphological or functional overlap with resident species, it will typically fail to establish due to severe symmetric competition for finite resources like nutrients, space, and light.

To quantify these dynamics, empirical focus shifted toward functional trait analysis. By measuring these observable morphological and physiological attributes, researchers could better predict an invader's capacity to exploit underutilized or entirely vacant niches within recipient ecosystems.

4. Contemporary approaches: invasion biology in the era of global change

Modern invasion science increasingly views biological invasions through the combined lenses of climate change and expanding global trade. Over the last few decades, the field has transitioned from descriptive cataloging of introduction events toward mechanistic inquiries into why species succeed or fail to colonize. Powered by macroecological datasets and high-performance computing, predictive models now simulate habitat fragmentation, shifting thermal baselines, and complex biophysical interactions (Mungi, N. A. et al., 2018). This trajectory mirrors a broader shift that began in the 1980s and 1990s, when the discipline traded qualitative case studies for rigorous, process-driven empirical designs. By the early 2000s, this evolution culminated in a deeply interdisciplinary approach that merged core ecological theory with genomics, climatology, socioeconomics, and behavioral science to map the spatial and temporal dynamics of invasions (Gaertner, M. et al., 2012). As a result, modern frameworks are continuously refined to tackle emerging biosecurity threats through advanced environmental monitoring.

This analytical refinement is urgently needed. While global frameworks like the IPBES rank invasive alien plants (IAPs) among the leading drivers of biodiversity loss, the accelerating scale of the crisis has prompted a comprehensive scientists' warning calling for immediate mobilization (Pyšek, P. et al., 2020). Navigating these disruptions requires a granular understanding of specific invasion mechanisms. Proactive horizon scanning, for example, allows researchers to anticipate how non-native species might bypass traditional ecological barriers before the damage is done (Seebens, H. et al., 2021). Such mechanistic foresight is vital in the era of global change. Driven by relentless trade and human mobility, models projecting the accumulation of alien species through 2050 warn that current management frameworks will soon face an unprecedented, continuous influx of new invaders (Ricciardi, A. et al., 2017). In this context, parsing these mechanistic pathways is no longer just an academic exercise—it is an operational prerequisite for mitigating future ecological collapse.

5. Guiding management and control efforts

Invasive alien plants (IAPs) frequently outcompete indigenous flora through superior nutrient-acquisition kinetics and rapid resource allocation. Pinpointing these specific physiological mechanisms allows land managers to deploy targeted resource-restriction strategies that arrest IAP expansion and kickstart native vegetative recovery. It was demonstrated that mapping edaphic nutrient fluxes is critical for designing successful mitigation frameworks (Funk, J. L. et al., 2007). In ecosystems altered by human-driven nutrient enrichment, aggressive non-native ruderals easily outpace native species, which are typically adapted to historical, low-resource baselines (Dukes, J. S. et al., 1999). Because these invaders are primed to rapidly capitalize on sudden resource pulses, manipulating soil fertility can tip the competitive balance back in favor of indigenous vegetation.

Designing these interventions requires tailoring the management strategy to the specific resource-exploitation pathways of the target invader. For instance, in soils overloaded with volatile macronutrients, land managers can apply external carbon sources like sawdust or mulch. This stimulates microbial nitrogen immobilization, reducing bioavailable nutrient levels and effectively starving nitrophilic IAPs from the system. Similarly, addressing agricultural runoff through modified field management and the installation of vegetative buffer strips can cut off the external fertilizer inputs that sustain invasive monocultures in nearby habitats. Shifting the paradigm from generalized eradication toward this type of mechanism-based resource manipulation ensures highly precise, process-driven ecological restoration.

6. Adapting to global environmental changes

Human-driven climate change and widespread environmental disruptions are actively accelerating biological invasions. Because invasive alien species (IAS) frequently possess high phenotypic plasticity and the capacity for rapid evolutionary adaptation, they exploit altered environments far more efficiently than their native counterparts. Mapping the mechanisms behind this range expansion is therefore critical for predicting future invasion trajectories and safeguarding native biodiversity under shifting global climate regimes. As early as 1999, Dukes and Mooney established that rising atmospheric carbon dioxide, escalating global temperatures, and altered rainfall patterns work in tandem to drive the establishment and proliferation of non-native taxa (Dukes, J. S. et al., 1999). These ongoing climatic shifts are systematically dismantling historical physiological barriers. As a result, invaders are now colonizing high-latitude and high-altitude ecosystems that were previously closed to them by cold limitations. Hellmann et al. (2008) later confirmed this dynamic, demonstrating that rising thermal baselines directly fast-track the expansion of invasive plants into historically inhospitable geographic zones (Hellmann, J. J. et al., 2008). As native communities face climate-induced physiological stress and demographic declines, opportunistic invaders move in rapidly to seize the resulting vacant niches.

To improve predictive accuracy, modern macroecological frameworks now anchor downscaled bioclimatic envelope models with empirical physiological stress data. By directly correlating an

invader's metabolic and reproductive tolerances with projected atmospheric trends, researchers can generate highly robust risk assessments. This predictive foresight is essential for transitioning conservation management away from reactive mitigation and toward proactive, biosecurity-focused interventions.

7. Interaction with climate change

Anthropogenic climate change—driven by rising temperatures, shifting precipitation regimes, and elevated atmospheric carbon dioxide—is systematically restructuring ecosystem composition and functionality. These macro-level environmental shifts alter both the spatial distribution and demographic dynamics of indigenous and invasive alien species (IAS). Specifically, warming trends are dismantling the historical thermal barriers that once restricted the survival of invasive taxa. As documented by Walther et al. (2002) and famously established by Parmesan and Yohe, rising global thermal baselines are driving directional, northward, and upslope migrations of aggressive non-native species into high-latitude and high-altitude regions that were previously too cold to support them (Walther, G. R. et al., 2002; Chapin III, F. S. et al., 2000). As native communities face mounting climate-induced physiological stress, their collective biotic resistance declines, leaving recipient ecosystems highly vulnerable to invasion. Under these perturbed conditions, opportunistic invaders move rapidly to displace native counterparts (Parmesan, C. et al., 2003). This pressure is further amplified by elevated atmospheric CO_2 concentrations, which directly modulate plant physiology—often accelerating the photosynthetic rates and biomass production of fast-growing, resource-efficient invasive genotypes at the expense of slower-growing native flora.

These demographic shifts inevitably rewrite foundational ecosystem processes. The resulting community turnover disrupts historical biogeochemical cycling and primary productivity loops. As Bradley et al. demonstrated, invasive range expansions do not merely displace native species; they actively modify soil nutrient dynamics, alter vegetative structural configurations, and fundamentally reorganize macro-level ecosystem functions (Bradley, B. A. et al., 2010). Navigating this crisis requires bridging empirical physiological tolerance thresholds with downscaled bioclimatic envelope models. By mapping future invasive trajectories under divergent climate scenarios, researchers can transition conservation frameworks away from reactive mitigation. Ultimately, this predictive foresight allows land managers to establish proactive biosecurity protocols and targeted landscape interventions, protecting vulnerable habitats before permanent community degradation sets in.

8. Advances in the physiology and resource acquisition strategies of invasive plants: Key studies and theories

Ever since Charles Elton's seminal 1958 monograph established the paradigm for modern invasion ecology (Elton, C. S., 1958), a central focus of the field has been elucidating the deterministic mechanisms that enable invasive alien plants (IAPs) to naturalize and dominate. While classical community assembly theory suggests that invaders succeed primarily by occupying vacant or underutilized niches (Simberloff, D., 2011), the reality on the ground is highly contested. Certain frameworks validate the biotic resistance hypothesis, which argues that species-rich native communities can effectively repel invaders (Higgins, S. I. et al., 2014). However, a growing body of counterevidence shows that successful IAPs often overcome this resistance through superior environmental tolerances (Funk, J. L. et al., 2017) and aggressive resource-acquisition kinetics (Leishman, M. R. et al., 2007). This aggressive strategy is particularly evident in nutrient-rich ecosystems. Here, non-native plants frequently outpace native flora through superior nutrient-use efficiency and rapid uptake rates (Godoy, O. et al., 2011; Steers, R. J. et al., 2011). They optimize their carbon investment by producing thin, resource-expensive leaves with high specific leaf area (SLA) (Griffin, K. L., 1994) and low construction costs per unit mass (Feng, Y. L. et al., 2009; Reich, P. B. et al., 1997)—physiological traits that place them squarely at the "acquire" end of the worldwide leaf economics spectrum (Wolkovich, E. M. et al., 2011). Yet, this high-return strategy has a clear trade-off: under severe resource limitation, slow-growing indigenous species often reclaim their competitive edge (Dukes, J. S. et al., 1999).

Beyond nutrient kinetics, IAPs leverage striking phenological and structural advantages. Many annual invaders display accelerated spring phenology, expanding their canopies early to monopolize spring light and soil moisture (Kimball, S. et al., 2011)—a development tightly linked to enhanced water-use efficiency (WUE) and extended reproductive phases (Funk, J. L. et al., 2010). Even under severe drought, specific ruderals can maintain vegetative elongation despite falling net carbon assimilation (Martin, P. H. et al., 2010). Similarly, in forested ecosystems, early-successional, shade-intolerant invasive trees exploit canopy gaps through rapid carbon fixation and high fecundity (Knapp, L. B. et al., 2000; Pattison, R. R. et al., 1998). Morphologically, they maximize photon capture by maintaining elevated leaf area ratios (LAR) and minimizing underground root biomass (Baruch, Z. et al., 2000; Lambers, H. et al., 2008), though this high photosynthetic capacity is sometimes offset by the steep metabolic costs of dark respiration (Van Kleunen, M. et al., 2010).

Underpinning all of these responses is high phenotypic plasticity. Compared to native species, IAPs typically exhibit far greater morphological and physiological flexibility in fluctuating environments (Steers, R. J. et al., 2011; Poorter, H. et al., 1986). This adaptive plasticity allows them to capitalize instantly on sudden resource pulses (Leishman, M. R. et al., 2005; Ignace, D. D. et al., 2007), a dynamic central to the fluctuating resources hypothesis (Dawson, T. E.,1993). For example, ecophysiological comparisons between the native grass *Heteropogon contortus* and the exotic *Eragrostis lehmanniana* demonstrate how plastic responses in predawn water potential and stomatal conductance allow the invader to dominate across contrasting sandy and clay soil profiles under altered rainfall regimes (Davidson, A. M. et al., 2011; Davis, M. A. et al., 2000). Sometimes, these physiological strategies interact in unexpected ways; for instance, deep-rooted invaders utilizing hydraulic lift can inadvertently facilitate neighboring vegetation during seasonal droughts by transferring groundwater to parched upper soil layers (Dawson, W. et al., 2011). Ultimately, macroecological assessments remind us that these traits do not operate in a vacuum. In high-resource environments like tropical forests, initial introduction effort (propagule pressure) can drive establishment and biomass amplification even more strongly than functional leaf or seed traits (Dawson, W. et al., 2012; DeFalco, L. A. et al., 2003). However, once established, aggressive exotic grasses systematically outcompete native counterparts by accelerating nitrogen immobilization, expanding their canopy architecture, and maintaining homeostatic growth regardless of environmental volatility (DiTommaso, A. et al., 1989). While artificial nutrient enrichment boosts overall primary productivity, it

invariably triggers a drop in community species richness due to this kind of asymmetric resource monopolization (Diffenbaugh, N. S. et al., 2005).

Today, these inherent physiological advantages are amplified by global change drivers. International trade networks act as a continuous global conveyor belt, introducing highly plastic species into entirely new geographic regions (Liu, Y. et al., 2017; Hulme, P. E., 2021). When these trade pathways intersect with climate change, they create highly unstable, shifting environmental baselines—uniquely positioning adaptable, fast-return invaders to thrive while less flexible native species decline.

To synthesize these diverse physiological mechanisms, the accompanying tables break down the functional distinctions between native and invasive flora.These physiological mechanisms highlight clear functional differences between native and invasive species (Tables 2–4). Specifically, Table 2 contrasts defining ecophysiological features, Table 3 maps life-history strategies to their ecological roles in recipient communities, and Table 4 outlines the specific survival mechanisms used during periods of severe resource stress.

Table 2: Contrasts the definitive ecophysiological features separating invasive species from native species.

Trait Category	Specific Trait	Invasive Species	Native Species	Ecological Advantage
Leaf Morphology	Leaf Mass per Area (LMA)	Low (e.g., 50–80 g/m²)	High (e.g., 100–150 g/m²)	Thinner leaves enable faster growth and shorter turnover time
Physiology	Photosynthetic Rate	High (15–25 µmol CO_2/m²/s)	Moderate to low (8–12 µmol CO_2/m²/s)	Faster carbon gain and growth in variable light conditions
Leaf Chemistry	Leaf Nitrogen Content	High (2.5–4.0%)	Moderate (1.5–2.5%)	High nitrogen supports higher photosynthesis and protein synthesis
Plasticity	Phenotypic Plasticity	High (responsive to light, water, nutrients)	Low to moderate	Allows flexible responses in fluctuating environments
Water Use	Water-Use Efficiency (WUE)	High	Variable	Maintains function in dry or resource-limited habitats
Phenology	Leaf Development Timing	Early and rapid	Seasonal, often delayed	Early resource capture and faster establishment

Table 3: Outlines key life-history traits and their broader ecological roles within recipient communities.

Specific Trait	What It Is (Definition)	Functional Role	Why It Benefits Invasive Species
Low Leaf Mass per Area (LMA)	The dry mass of a leaf divided by its area (g/m²); thinner, cheaper leaves.	Enables rapid leaf production and turnover.	Allows fast resource capture and short lifespan investment—ideal for quick growth.
High Photosynthetic Rate	The speed at which a leaf converts light and CO_2 into sugars (µmol CO_2/m²/s).	Supports rapid biomass accumulation.	Enhances competitive ability in both high and low light environments.
High Leaf Nitrogen Content (LNC)	Amount of nitrogen per unit leaf mass (%).	Boosts the efficiency of photosynthesis (as N is a component of Rubisco enzyme).	Facilitates faster growth and energy production.
High Phenotypic Plasticity	The ability of a plant to alter its traits (e.g., leaf size, root length) in response to the environment.	Allows survival and function across a range of conditions (light, water, nutrients).	Increases adaptability, especially in disturbed or changing environments.
High Water-Use Efficiency (WUE)	The amount of carbon gained (photosynthesis) per unit of water lost (transpiration).	Maintains growth even when water is scarce.	Allows expansion into drier or water-limited habitats.
Early Leaf Development / Early Phenology	Producing leaves and starting growth early in the season or life cycle.	Secures access to light and nutrients before others.	Gets a “head start” on resource capture and space occupation.
Fast Growth Rate	Rapid increase in plant size or biomass.	Outcompetes slower plants for light and nutrients.	Leads to quick canopy formation and dominance.

Table 4: Highlights specific physiological survival mechanisms utilized by invaders during periods of severe resource limitation.

Trait	Functional Role	Benefit in Low-Resource Systems
Low LMA	Fast resource turnover	Quick leaf production and turnover
High photosynthetic rate	Maximized carbon gain	Supports high growth even with limited light
High leaf nitrogen	Enhanced photosynthetic machinery	More Rubisco enzymes and higher productivity
High plasticity	Flexibility in morphology and physiology	Survives across varied microhabitats
High WUE	Efficient water use	Thrives under drought or low rainfall
Early phenology	Establishment before competitors	Gains early access to light, nutrients
Fast growth rate	Quick canopy dominance	Outcompetes slower-growing natives

9. Impact of environmental factors on invasive species: insights from recent studies on climate, resource use, and adaptation

Global macroclimatic shifts driven by greenhouse gas emissions interact dynamically with localized topography to trigger severe meteorological variations (Drenovsky, R. E. et al., 2012). Features like coastal boundaries and montane configurations alter local convective orographic activity, driving intense precipitation shifts that test the limits of plant communities. Within these unstable environments, successful invasive alien plants (IAPs) leverage rapid functional and phenotypic adaptations to expand across novel geographic fronts (Drenovsky, R. E. et al., 2008). A primary theater of this competitive dominance is the manipulation of edaphic nitrogen (N). In resource-replete environments, IAPs consistently outpace native flora by utilizing soil nitrogen far more efficiently (Hoopes, M. F. et al., 2002), thereby directly altering reproductive fitness, survival parameters, and population density in vulnerable biomes such as grasslands (Evans, J. R.,1989). At the cellular level, this advantage hinges on leaf nitrogen concentrations, which dictate net photosynthetic capacity. Under closed forest canopies—such as subtropical *Araucaria* forests—light attenuation establishes a harsh physiological barrier, forcing understory flora to dynamically adjust leaf thickness, specific leaf area (SLA), and foliar nitrogen partitioning (Eliáš, P., 2014; Funk, J. L., 2008). Here, high-performing invaders outcompete native species by prioritizing nitrogen allocation to thylakoid structures to optimize photon capture under deep shade (Emer, C. et al., 2011).

When light and water limitations hit simultaneously, the ecophysiological divergence between native and non-native taxa becomes even more pronounced (Martin, P. H. et al., 2010). High phenotypic and functional plasticity allows exotic genotypes to rapidly recalibrate vital traits in response to environmental volatility (Funk, J. L., 2010). During seasonal droughts, for example, native species often sustain far greater tissue damage than their invasive counterparts; successful invaders frequently conserve energy by reducing structural investments in mechanical defense (Fridley, J. D., 2012). Furthermore, in temperate zones, IAPs exploit extended phenological windows, maintaining active carbon assimilation late into autumn, long after the native canopy has senesced (Foxcroft, L. C. et al., 2011; Firn, J. et al., 2012).

Quantifying these functional traits—including SLA, leaf dry matter content (LDMC), and photosynthetic light-use efficiency—confirms that managing resource supply loops can actively suppress invasive performance (Feng, Y. et al., 2007). The superior growth rates of these exotic species are rooted in heritable genetic advantages (Reich, P. B. et al., 1997) that facilitate rapid photo-acclimation and enhanced quantum yield across shifting irradiance gradients (Funk, J. L. et al., 2013). Interestingly, this dominance relies on optimized internal allocation: IAPs preferentially partition foliar nitrogen toward structural growth rather than light-harvesting components (Funk, J. L. et al., 2010).

These light-dependent resource requirements make invaders highly sensitive to micro-environmental shifts, providing a clear window for targeted ecosystem restoration (Gleason, S. M. et al., 2004). This vulnerability is evident in insular ecosystems like Hawaii, where endemic trees such as *Acacia koa* suffer severe competitive suppression when paired with aggressive invaders such as *Fraxinus uhdei*, which outcompete native species by rapidly locking down carbon and nitrogen pools (Givnish, T. J., 1988). Across isolated island systems, shifting light gradients drive structural and functional diversification of photosynthetic trait suites within evolving lineages (Givnish, T. J. et al., 2004; Gebauer, R. L. et al., 2000). These resource-acquisition dynamics leave distinct stable carbon isotope (δ13C) signatures that reflect the plant's integrated water- and nitrogen-use efficiencies as energy flows through primary productivity pathways (Feng, Y. L. et al., 2009; Valladares, F. et al., 2002).

While quantitative assessments of pristine communities reveal clear niche differentiation—where canopy giants like *Quercus* maximize carbon assimilation in high light and shade-adapted species like *Fagus* optimize photon capture below (Güsewell, S. et al., 2002)—exotic invaders break these rules. They maintain high carbon fixation rates across both resource-poor and resource-rich environments (Steers, R. J. et al., 2011). This rule-breaking extends into aquatic systems; in wetland ecosystems, where macrophyte communities regulate their nutrient configurations based on bioavailable edaphic pools (Güsewell, S., 2004), human-driven eutrophication via nitrogen or phosphorus inputs shifts the internal stoichiometry of the vegetative community. The resulting alteration of tissue N:P ratios fundamentally reorganizes ecosystem structure in favor of the invader (Gross, K. L. et al., 2005).

10. Resource utilization and growth strategies in invasive vs. native plants: Key findings and insights from recent research

In oligotrophic grassland ecosystems, invasive alien plant (IAP) colonization depends on a tight intersection between fluctuating resource availability and propagule pressure (Grotkopp, E. et al., 2007). While shifts in soil nutrient profiles or canopy light attenuation rewrite community assembly, the specific taxa that successfully establish depend on the precise nature of the environmental filter. For example, woody invaders frequently exploit high-irradiance, arid conditions by leveraging an elevated specific leaf area (SLA) to accelerate seedling growth (Harrison, M. T. et al., 2009). Yet this strategy imposes a stark evolutionary trade-off: intensive structural investment in thick cell walls in foliar tissue can sequester nitrogen, thereby reducing the metabolic resources available for photosynthetic carbon assimilation (Preston, K. A. et al., 2003; Olde Venterink, H., 2011). This balance between rapid vegetative growth and strict water conservation dictates spatial distributions across heterogeneous landscapes (Huenneke, L. F. et al., 1990; Matzek, V., 2012). In Mediterranean-climate meadows, such as those in California, exotic annual grasses routinely displace indigenous vegetation across flat topographies; however, on rocky, shallow soils, endemic chasmophytes maintain a competitive advantage by utilizing specialized stomatal architecture and stem elongation patterns to survive alternating periods of deluge and drought Huxman, (T. E. et al., 2008; Harrington, R. A. et al., 1989).

When resource limitations tighten, stress-tolerant invasive grasses remain competitively equal to native species. The introduction of sudden nutrient pulses, however, allows these exotics to achieve asymmetric growth acceleration (Foxcroft, L. C. et al., 2011). Interestingly, meta-analytical data across the worldwide leaf economics spectrum reveal a fascinating nuance: while exotic genotypes exhibit higher overall growth rates, they do not differ significantly from native species in their maximum mass-specific net carbon assimilation rates (Godoy, O. et al., 2011; Brock, M. T. et al., 2005). Instead, their dominance is driven by a tighter integration of functional trait suites, superior resource-use efficiencies, and IAP-induced modifications to localized nitrogen cycling that optimize the invader's nutrient return loops (Laungani, R. et al., 2009; Leishman, M. R. et al., 2007).

Under acute abiotic stress, these traits diverge dynamically. For instance, beneath the closed forest strata of insular landscapes such as Oahu, non-native flora exhibit accelerated leaf economic strategies that occupy entirely distinct eco-functional spaces from those of native communities (Penuelas, J. et al., 2010; Janse-Ten Klooster, S. H. et al., 2007). Concurrently, shade-tolerant invasive understory species display highly coordinated correlations between leaf display patterns, petiole flexibility, and stem mechanical stability to maximize photon capture (James, J. J. et al., 2011).

In contrast, desert invaders rely on dense foliar pubescence to increase boundary-layer resistance and reflect excess solar radiation, balancing transpirational water loss with metabolic energy production (Knapp, A. K. et al., 2008). Where ancient, highly weathered landscapes host specialized endemic flora that use localized mining mechanisms—such as *Lupinus* species that develop specialized cluster roots to exude carboxylates and extract tightly bound phosphorus (Lambers, H. et al., 2013; Lusk, C. H. et al., 2007)—invasive lineages bypass these constraints. They exploit elemental stoichiometry (C:N:P ratio) to link subcellular biochemical processes directly to macro-level ecosystem dynamics, maintaining high carbon fixation rates across both resource-poor and resource-rich environments (Steers, R. J. et al., 2011; Ordonez, A. et al., 2013).

Underpinning this ecological versatility is an unmatched capacity for adaptive phenotypic plasticity (Ignace, D. D. et al., 2007; Laungani, R. et al., 2009). While certain native dandelions (*Taraxacum* spp.) maintain structural integrity during prolonged drought, they exhibit lower plastic adjustments in water-use efficiency than their highly aggressive, invasive congeners (Elser, J. J. et al., 1996). This capacity for functional acclimation allows IAPs to dynamically recalibrate their physiological phenotypes in response to volatile fertilizer levels, moisture shocks, and high-irradiance stress across diverse microclimatic zones (Matzek, V., 2012; Hu, W. et al., 2016; Zunzunegui, M. et al., 2011).

Driven by global change, these traits interact deterministically with macroecological resource loops to govern invasion dynamics [Keane, R. M. et al., 2002; Bellard, C. et al., 2016; Leffler, A. J. et al., 2011]. These disruptions are amplified by climate change, which alters local microclimates and resource availability, favoring aggressive colonizers over native flora. New geospatial tools, such as global soil temperature maps, show exactly how macroclimatic warming alters ground-level conditions (Gioria, M. et al., 2023). However, significant research gaps remain regarding how these belowground microclimatic shifts interact with aboveground multitrophic dynamics over time. Resolving these ambiguities is vital; it allows researchers to synthesize complex evolutionary traits with real-world environmental stressors to predict the next wave of ecological shifts (Lembrechts, J. J., et al., 2021).

Ultimately, modeling these flexible trait responses across broad geographic scales is an operational necessity (Mungi, N. A. et al., 2019; Mungi, N. A. et al., 2020), particularly because biological invasions impose severe socio-economic consequences and substantial financial burdens on public infrastructure and agricultural production (Mungi, N. A. et al., 2021; Nuñez, M. A. et al., 2020). To precisely map these

underlying physiological stress responses, modern frameworks rely on advanced bioenergetic indicators:
Chlorophyll *a* fluorescence metrics (Kalaji, H. M. et al., 2012) to capture real-time photosynthetic efficiency.
Polyphasic OJIP transient analysis (Zivcak, M. et al., 2013), to isolate electron transport dynamics within photosystem II (PSII) (Mathur, S. et al., 2014).

As structural models show, these integrated ecophysiological mechanisms consistently enable non-native plant genotypes to maintain superior nitrogen-use efficiency relative to sympatric indigenous vegetation (**Figure 1**).

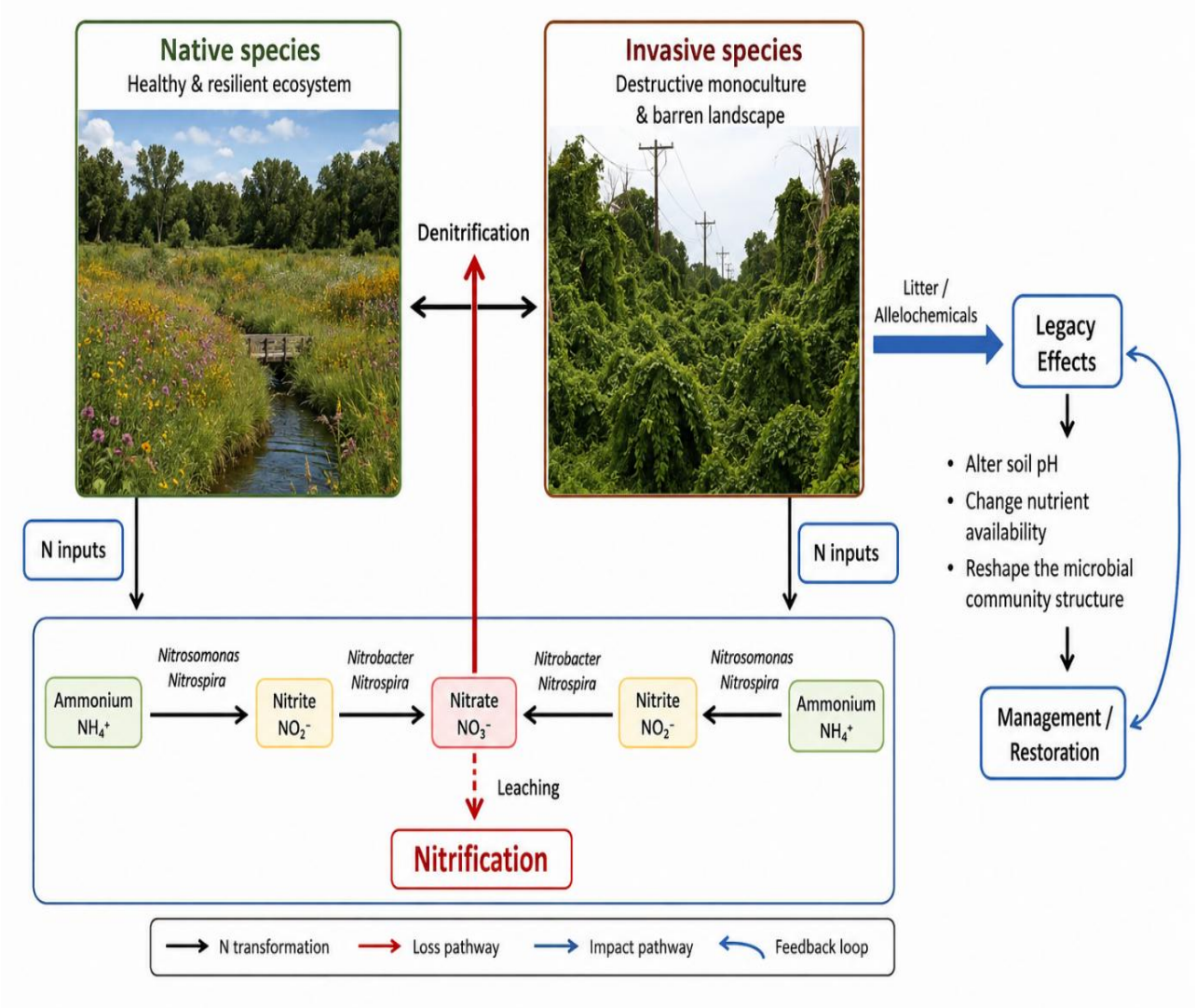

Figure 1. A diagram representing the mechanism through which IPS impacts the nitrogen cycle of the present ecosystem and affects native plant species and their health. Images used in this figure were created by Gemini AI (https://gemini.google.com/app)

11. Invasive plant species research in India: Progress, GAPS, and the need for physiological insights

While biological invasion dynamics have been rigorously investigated globally since the mid-twentieth century, substantial regional knowledge gaps persist across the Indian subcontinent. Quantitative research exploring the ecophysiological mechanisms and functional traits of invasive alien plants (IAPs) within unique Indian ecosystems remains surprisingly scarce. Historically, domestic literature has prioritized observational floristic inventories, tracking regional distributions, and taxonomic cataloging, leaving empirical field experiments and mechanistic inquiries heavily underrepresented.

This is not to diminish the substantial baseline frameworks that underpin regional invasion biology. Early macroecological assessments successfully mapped biological invasions across South Asia (Saxena, M. K., 2000), laying the groundwork for comprehensive national checklists that identify and catalog non-native flora across India (Reddy, C. S., 2008). Over the past two decades, these classification systems have been systematically updated, yielding highly resolved spatio-

temporal datasets and functional groupings for invasive alien species across highly diverse landscapes (Khuroo, A. A. et al., 2008; Khuroo, A. A. et al., 2011; Khuroo, A. A. et al., 2012; Khuroo, A. A. et al., 2021). More recently, these research trajectories have expanded into high-altitude environments, offering detailed spatial mappings of invasive distributions within vulnerable montane ecosystems (Pathak, R. et al., 2019). Concurrently, targeted autecological and management-driven studies have scrutinized aggressive, high-impact invaders—most notably *Lantana camara* and *Parthenium hysterophorus*—to uncover their bioclimatic tolerances, phenotypic traits, allelopathic behaviors, and potential classical biocontrol agents.

Yet, despite these taxonomic and spatial milestones, a critical empirical blind spot remains. We still lack a precise understanding of the ecophysiological strategies governing IAP naturalization and demographic dominance in Indian forest ecosystems, particularly under severe resource limitation. Specifically, there is an acute shortage of data detailing how these non-native genotypes dynamically regulate water-use efficiency (WUE), photosynthetic light-harvesting capacity, and internal nitrogen stoichiometry under acute environmental stress.

Bridging these functional trait behaviors is an operational prerequisite for building predictive biosecurity models. Until domestic research transitions from descriptive checklists toward process-driven ecophysiological investigations, designing targeted, proactive landscape management frameworks and optimized ecological restoration protocols for India's vulnerable ecosystems will remain out of reach.

12. Management of invasive plant species

Biological invasions by invasive alien plants (IAPs) are a leading driver of global ecological degradation. Facilitated by both intentional introductions and accidental transport pathways, these non-native genotypes naturalize rapidly within recipient ecosystems. Once established, IAPs exert intense competitive pressure on indigenous flora, triggering competitive exclusion and subsequent crashes in local biodiversity. This systematic displacement fundamentally shifts community architecture, rewires trophic webs, and destabilizes historical ecosystem properties.

Mitigating these complex threats requires moving away from isolated, reactive eradication toward integrated pest management (IPM) frameworks that synthesize mechanical, chemical, biological, and cultural controls. Crucially, effective landscape-level mitigation depends on aligning these interventions with the invasion curve paradigm, recognizing that management efficiency and cost-effectiveness scale inversely with the invasion's temporal and spatial progression.

12.1 Strategic Phases of the Invasion Control Pipeline

12.1.1 Pre-Introduction Biosecurity and Exclusion

Proactive exclusion is the most cost-effective and ecologically viable strategy. Implementing rigorous phytosanitary regulations and restrictive import protocols limits the introduction of potential invasive propagules at national borders. This strategy relies on targeted surveillance of high-risk trade vectors combined with strict biosecurity checks. Concurrently, public awareness campaigns are vital for altering consumer behavior and minimizing the deliberate dissemination of high-risk ornamental exotics.

12.1.2 Early Detection and Rapid Response (EDRR)

Following a biosecurity breach, the immediate execution of an Early Detection and Rapid Response (EDRR) protocol is critical. The temporal window following IAP establishment dictates the probability of successful control. Executing aggressive, localized eradication campaigns during this initial colonization phase maximizes the probability of eliminating the founder population before the species achieves exponential range expansion.

12.1.3 Long-Term Containment and Impact Mitigation

When an IAP exceeds the threshold for feasible eradication, strategic objectives must shift from total elimination to long-term asset protection and population containment. Management designs focus on suppressing invader density beneath established economic and ecological injury thresholds, while establishing physical or chemical barriers to block further range expansion into uninvaded territories.

Deciding when and where to deploy these phases requires addressing not only ecological damage but also the profound socio-economic trade-offs involved, particularly since long-term IAP proliferation severely degrades human well-being and local livelihoods (Shackleton, R. T., et al., 2019). To streamline these decisions, modern biosecurity protocols rely on systematic risk assessment frameworks designed to identify critical habitats vulnerable to invasion before extensive displacement occurs (Shackleton, R. T., et al., 2019).

However, standard static protocols often fail when deployed in isolation. This operational gap underscores the necessity of adapting to global environmental changes, which demands dynamic strategies that integrate climate change projections directly into invasive species management to prevent historical eradication models from becoming obsolete (Tuttle, L. J., et al., 2022; Kumschick, S. et al., 2020). Ultimately, establishing adaptive control pipelines that unite socio-economic impacts, predictive spatial mapping, and shifting climate baselines is a prerequisite for maintaining resilient ecosystems.

A critical, often overlooked phase within this management framework is post-eradication ecological restoration. Passive containment frequently results in secondary biological invasions or the rapid re-establishment of the primary target weed from persistent soil seed banks. In contrast, active restoration involves the intentional reintroduction of indigenous functional types to accelerate successional development and maximize biotic resistance. By quickly occupying vacant vegetative niches and optimizing resource-consumption loops, restored native communities effectively stabilize ecosystem functions and armor the landscape against subsequent reinvasion.

13. Control techniques

Mitigating the proliferation of invasive alien plants (IAPs) requires a shift from isolated eradication to a multifaceted Integrated Pest Management (IPM) framework. IPM coordinates mechanical, chemical, biological, and cultural methodologies to systematically suppress invasive

populations while minimizing non-target ecological damage. The strategic allocation of these control tactics depends on the life history of the target species, the scale of the infestation, and localized environmental sensitivities. By synthesizing these diverse methodologies, land managers can reduce their reliance on single-agent control practices, thereby mitigating the risk of management failure or secondary biological invasions.

13.1 The IPM Control Toolkit

13.1.1 Mechanical and Physical Control

This approach involves the direct physical removal or destruction of invasive vegetation. Standard methods include manual hand-pulling for low-density infestations, targeted mowing to reduce aboveground biomass and disrupt seed production, and prescribed burn regimes to clear expansive, high-density monocultures. While labor-intensive, mechanical control remains indispensable in environmentally sensitive zones where chemical use is restricted. For instance, the manual extraction of *Alliaria petiolata* (garlic mustard) from temperate forest understories is a standard practice used to protect native herbaceous layers.

13.1.2 Chemical Control

Chemical control relies on targeted herbicide applications to achieve rapid weed mortality, serving as a highly effective tool for broad-scale infestations or for perennial species with extensive subterranean root networks. Application methods include foliar sprays for broad vegetative coverage, cut-stump applications to inject systemic chemicals directly into the vascular systems of woody species, and basal bark treatments. The choice of compound and deployment technique depends on the target taxon's physiology, local soil conditions, and potential ecotoxicological impacts on co-occurring native species.

13.1.3 Biological Control

Biological control introduces host-specific natural enemies—such as phytophagous insects, mites, or specialized pathogens—sourced from the invader's native range. The primary goal is never absolute eradication, but rather the long-term suppression of the IAP population beneath established economic and ecological injury thresholds. Because this is a self-sustaining landscape strategy, it requires extensive pre-release screening to guarantee host specificity and eliminate non-target risks. A classic paradigm is the deployment of the leaf-feeding chrysomelid beetle (*Galerucella calmariensis*) to suppress the invasive wetland macrophyte *Lythrum salicaria* (purple loosestrife).

Case studies tracking high-impact IAPs—such as the coordinated containment of *Heracleum mantegazzianum* (giant hogweed) in the United Kingdom or the long-term suppression strategies for *Reynoutria japonica* (Japanese knotweed)—demonstrate that no single control methodology is universally sufficient. Effective landscape management requires a site-specific, adaptive approach tailored to the unique reproductive biology of the target invader and prevailing environmental conditions.

Operational protocols must prioritize pre-introduction biosecurity and Early Detection and Rapid Response (EDRR) systems to eliminate emerging invasive foci before naturalization occurs. Following the initial suppression phase via combined mechanical, chemical, and biological tools, post-treatment monitoring and active ecological restoration become mandatory. Repeated monitoring and the active reintroduction of native functional types maximize community biotic resistance. Ultimately, this active stewardship reduces long-term management expenditures, stabilizes trophic structures, and arms the ecosystem against subsequent reinvasion loops.

For a structured, step-by-step breakdown outlining the progression of operational stages, targeted execution parameters, and post-treatment monitoring protocols necessary to implement this integrated management strategy, see Table 5.

Table 5: Methods for Controlling Invasive Species

Method	Description	Techniques & examples	Advantages	Disadvantages
Physical/ Manual	Directly removing the invasive species by hand or with simple tools. Best for small-scale infestations.	Hand-pulling: Removing small plants and their roots. Digging: Using shovels or forks to remove larger plants or root systems. Flooding/Drawdown: Manipulating water levels to kill terrestrial or aquatic species. Trapping/Hunting: Capturing or culling invasive animals.	Minimal environmental impact, doesn't use chemicals, provides immediate results for small areas.	Very labor-intensive, can be costly for large areas, often only temporary if the entire plant or organism isn't removed.
Mechanical	Using machinery or tools to control the species. Suitable for larger infestations.	Mowing/Cutting: Repeatedly cutting down plants to deplete their energy reserves and prevent seeding. Tilling: Turning the soil to destroy plant roots and bury plant parts. Girdling: Removing a ring of bark from a tree trunk to starve the root system. Dredging: Removing aquatic plants and sediment from a waterbody.	Can be more efficient than manual methods for large areas, doesn't rely on chemicals.	Can be expensive and disruptive to the soil or ecosystem. Mowing can spread seeds if done at the wrong time.

Chemical	Using pesticides or herbicides to kill or inhibit the growth of the invasive species.	Foliar Spray: Applying chemicals directly to the leaves of a plant. Cut-Stump Treatment: Applying herbicides to a freshly cut stump to prevent regrowth. Basal Bark Treatment: Spraying the lower portion of a woody plant's trunk with herbicide. Injecting: Injecting herbicide directly into the stem or trunk of a plant.	Highly effective and efficient for widespread infestations, can be a cost-effective solution.	Can harm non-target native species, potential for environmental contamination (soil and water), requires careful handling and application, may lead to resistance in invasive populations.
Biological	Introducing a species' natural enemies (biocontrol agents) from its native habitat to control its population in the new environment.	Introducing insects, pathogens, or other organisms that feed on or parasitize the invasive species. For example, using the weevil Aculus hypericifoliae to control the invasive St. John's Wort.	Long-term, self-sustaining control with minimal human intervention; highly specific and generally has low impact on native species.	Requires extensive research and testing to ensure the biocontrol agent doesn't become invasive itself or harm non-target species. The effects can be slow and may not result in full eradication.

14. Conclusions and future perspectives

A systems-level conceptual framework illustrates the sequential life cycle of biological invasions by non-native plant species, mapping the progression from initial environmental drivers to subsequent ecological impacts and management responses. This process is driven by macro-level factors, with global trade and human mobility serving as the primary vectors of introduction. When these pathways intersect with landscape fragmentation and climate change indicators—such as rising temperatures, altered rainfall patterns, and elevated CO2—they create highly disturbed, vacant niches. Invasive plants aggressively exploit these open spaces by leveraging distinct physiological advantages along the "fast-return" end of the worldwide leaf economics spectrum. These traits include low leaf mass per area (LMA), superior photosynthetic capacity, high nitrogen-use efficiency, high phenotypic plasticity, and early phenology. These metabolic advantages are further reinforced by ecological strategies such as enemy release, novel allelopathic weapons, and rapid evolution toward greater competitive ability.

Once established, these species trigger cascading, multi-level ecosystem impacts. They drive severe biodiversity loss by displacing indigenous flora and disrupting local trophic webs, while simultaneously altering biogeochemical regimes, soil nutrient fluxes, and hydrologic profiles. Ecologists rely on a few core frameworks to make sense of these aggressive takeovers. Take the Enemy Release Hypothesis, for example: it argues that when an invader leaves its native predators behind, it can stop wasting energy on defense and pour those resources straight into growth. Over time, this shift can trigger the Evolution of Increased Competitive Ability (EICA), in which introduced populations evolve to outcompete the locals. If that isn't enough, some invaders bring chemical warfare into the mix—the Novel Weapons Hypothesis highlights how they release allelopathic toxins to actively suppress neighboring plants. On the flip side, whether an invasion succeeds often comes down to a numbers game and the local neighborhood: Biotic Resistance examines how diverse native communities can block newcomers, while Propagule Pressure measures how often the invader is introduced to the area (Table 6). The resulting multi-sector socio-economic damage ranges from sharp declines in crop yields and infrastructure degradation to public health risks posed by potent airborne allergens. Mitigating these systemic disruptions demands a structured, step-by-step management approach. Protocols must prioritize upfront biosecurity exclusion and Early Detection and Rapid Response (EDRR) systems, transition into integrated pest management (IPM) strategies that coordinate mechanical, chemical, and biological controls, and conclude with the strategic replanting of native functional types to secure long-term ecological restoration and community resilience.

While the extensive global body of literature on biological invasions has successfully unraveled these multi-scale interactions, a significant geographic disparity persists within macroecological research. The ecological impacts, traits, and long-term management strategies for invasive alien plants (IAPs) have been rigorously characterized across Mediterranean-climate ecosystems, North American annual grasslands, and diverse tropical biomes. In contrast, understudied regions like the Indian subcontinent lack comparable empirical depth.

Contemporary invasion science within India has relied primarily on descriptive floristic checklists, localized distribution surveys, and observational indexing. Consequently, there is an acute deficit of empirical, experimental data addressing the underlying physiological mechanisms driving regional invasiveness. This empirical knowledge gap is especially pronounced across low-resource or highly fluctuating soil environments, where invasive genotypes deploy specialized structural and metabolic adaptations to achieve demographic dominance. While domestic mapping initiatives have successfully cataloged regional IAP presence, the scarcity of mechanistically driven ecophysiological research limits our understanding of the precise kinetics that govern range expansion and competitive exclusion within native plant communities.

To resolve these ambiguities, future research trajectories within the Indian subcontinent must transition away from descriptive cataloging and toward controlled, manipulative experiments. Quantifying resource-acquisition kinetics, tissue-level nutrient allocation, and phenotypic plasticity

profiles under acute environmental stress is no longer just an academic exercise—it is the defining requirement for predicting, preventing, and managing the next wave of ecological shifts across the subcontinent

Table 6: Theories of Invasive Species Success

Theory	Description	Key Mechanism	Examples & References
Enemy Release Hypothesis (ERH)	Invasive species are successful because they escape their natural predators, parasites, and pathogens from their native range. This "release" allows them to reallocate resources from defense to growth and reproduction, giving them a competitive advantage.	Release from specialist enemies (e.g., host-specific herbivores or diseases).	The invasive purple loosestrife (*Lythrum salicaria*) in North America has fewer natural enemies than it does in its native European range, which contributes to its prolific growth and spread. (Blossey & Notzold, 1995)
Evolution of Increased Competitive Ability (EICA)	An evolutionary extension of the Enemy Release Hypothesis. It posits that over time, invasive species evolve in their new environment. Because they don't need to invest energy in costly defenses against absent enemies, they evolve to allocate more resources to traits that enhance their competitive ability, such as faster growth, higher biomass, and increased seed production.	Evolutionary shift in resource allocation from defense to growth.	Studies on garlic mustard (*Alliaria petiolata*) have shown that North American populations grow faster and produce more seeds than their European counterparts, supporting the idea of an evolutionary change in the introduced range. (Bossdorf et al., 2005)
Novel Weapons Hypothesis (NWH)	Invasive species outcompete natives by producing biochemical compounds that native species have not encountered and are not adapted to. These "novel weapons" can be allelopathic chemicals that inhibit the growth of native plants or other toxins that harm native animals.	Introduction of new biochemicals that native species are not equipped to defend against.	Spotted knapweed (Centaurea stoebe) releases a compound called catechin that can kill native plants and bacteria in the soil. (Bais et al., 2003)
Propagule Pressure Hypothesis	The success of an invasive species is directly related to the number of individuals introduced and the frequency of introductions. The more seeds, spores, or individuals that are introduced to a new area, the greater the chance that some will establish, survive, and overcome any initial environmental resistance.	High number and frequency of introductions.	Many successful invasive plants, like cheatgrass (*Bromus tectorum*), were introduced repeatedly and in large quantities, increasing the likelihood of successful establishment.
Biotic Resistance Hypothesis	This theory suggests that diverse and species-rich native communities are more resistant to invasion. They provide strong competition and fill available niches, making it difficult for an invader to establish. Conversely, disturbed or species-poor communities are more vulnerable to invasion.	Strong competition and niche preemption from native species.	Disturbed areas like agricultural fields or forests cleared by logging are often more susceptible to invasion because native species are not there to provide a barrier to establishment. (Elton, 1958)

Declarations

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Clinical Trial Number

Not applicable.

Consent to Publish

Not applicable.

Consent to Participate

Not applicable.

Ethics Declaration

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Author Contributions

PS and VK conceptualized the article. PS, KP, MA, and RK contributed to the writing and finalization of the manuscript.

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Supplementary material

Supplementary material presents representative images of the major invasive plant species discussed in this review. Also, full source information and attribution details for each image are provided

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