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Invasion patern and distribution of *Parthenium hysterophorus* (Congress grass) across diferent agroclimatic zones of India

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Abstract
How far has *Parthenium hysterophorus* spread across the diverse agroclimatic regions of India, and what factors drive its invasion success? This research examined the invasion patern and spatial distribution of *P. hysterophorus*, commonly known as Congress grass, across eight agroclimatic zones of India through a systematic review and geospatial analysis of published field surveys, herbarium records, and satellite-derived vegetation indices. Data were compiled from 127 peer-reviewed sources spanning 2001 to 2022, covering arid, semi-arid, sub-humid, humid tropical, sub-tropical, transitional, coastal, and per-humid zones. Plant density, percentage ground cover, and frequency of occurrence served as the main distribution metrics. The sub-humid Indo-Gangetic Plains recorded the highest plant density at 43.6 plants per square metre with 38.1 per cent ground cover, followed by the transitional Central Highlands at 37.2 plants per square metre. Arid zones of western Rajasthan and per-humid areas of the north-east showed the lowest colonisation levels, at 12.3 and 8.4 plants per square metre, respectively. Dispersal pathway analysis pointed to anthropogenic corridors such as road networks, railway lines, and contaminated grain movement as the chief vectors driving range expansion beyond natural wind and water dispersal. Species diversity indices in heavily invaded sites were 34.7 per cent lower than in non-invaded reference plots, confirming a negative relationship between *P. hysterophorus* density and native plant richness. Temperature, rainfall seasonality, and soil disturbance history emerged as the strongest environmental predictors of invasion intensity. These results provide a zone-wise baseline that can guide targeted management and biocontrol strategies for this aggressive alien weed across the Indian subcontinent.

Keywords: Parthenium hysterophorus, invasion ecology, agroclimatic zones, weed distribution, congress grass, spatial analysis, biodiversity impact, invasive alien species, dispersal pathways, geospatial mapping

Introduction

Can a single herbaceous weed reshape the agricultural and ecological landscape of an entire subcontinent? The spread of *Parthenium hysterophorus L.* (Asteraceae), popularly called Congress grass, across the Indian subcontinent ofers a troubling answer. First detected near Pune in 1956 as a contaminant in PL-480 wheat consignments from the United States, this annual herb has since colonised nearly every Indian state, moving from waste lands and roadsides into crop fields, pastures, and forest margins [1, 2].

India spans 15 recognised agroclimatic zones that range from hyper-arid deserts in the west to per-humid evergreen tracts in the north-east [3]. Each zone presents a distinct combination of rainfall, temperature, soil texture, and land-use intensity. And yet *P. hysterophorus* has managed to establish self-sustaining populations in most of them, though with markedly unequal success [4]. Understanding why certain zones carry dense infestations while others remain only lightly afected is a prerequisite for designing zone-specific management plans rather than relying on a blanket approach.

Earlier work mapped the weed at state or district scales. Gnanavel (2013) [5] catalogued its occurrence records from herbarium sheets and published floras, while Shabbir and Bajwa (2006) [6] assessed its distribution in the context of Punjab province [5, 6]. But few investigations have overlaid distribution data onto an agroclimatic framework, which is more meaningful than administrative boundaries because it captures the environmental gradients that govern plant establishment. A spatially explicit, zone-by-zone comparison of plant density, ground cover, and frequency of occurrence has been lacking. Several dispersal vectors have been implicated. Wind carries the lightweight achenes short distances, and floodwater moves them along river courses during monsoon months [7].

Anthropogenic corridors, however, appear to be the main driver of long-range spread. Road and railway embankments act as linear habitats that funnel the weed into new territory, and contaminated grain shipments repeatedly introduce it to grain markets and milling sites [8]. Disentangling the relative importance of these pathways for each zone remains an open question.

The consequences of invasion extend well beyond crop yield loss. Dense *P. hysterophorus* stands suppress native herbaceous species through allelopathic interference and sheer competitive dominance, altering community composition in grasslands, riverine tracts, and degraded forest understorey [9]. Livestock that feed on the weed develop dermatitis, while pollen exposure in farming communities triggers allergic rhinitis and contact dermatitis [10]. Economic estimates place the annual damage in parts of southern India at several hundred crore rupees when healthcare, fodder loss, and yield penalties are combined [11].

Against this backdrop, the present research set out to (a) compile published records of *P. hysterophorus* occurrence from across India into a unified geospatial database, (b) quantify plant density, ground cover, and frequency for each agroclimatic zone, (c) identify the principal dispersal pathways contributing to inter-zonal spread, and (d) evaluate the impact of invasion on local plant species diversity. By framing the invasion through an agroclimatic lens, the findings aim to support prioritisation of control eforts in the zones where the weed is spreading fastest and causing the greatest harm.

Material and Methods

Study Area Description

The research covered the entire Indian landmass between 8° 4′ N and 37° 6′ N latitude and 68° 7′ E and 97° 25′ 1 E longitude. India's diverse geography was divided into eight broad agroclimatic zones for this analysis, following the Planning Commission classification: Arid (western Rajasthan, Kutch), Semi-Arid (Deccan Plateau and parts of Telangana), Sub-Humid (Indo-Gangetic Plains from Haryana through Bihar), Humid Tropical (Western Ghats, Malabar Coast), Sub-Tropical (Shivalik foothills, outer Himalaya), Transitional (Central Highlands of Madhya Pradesh and Chhatisgarh), Coastal (Eastern seaboard from Tamil Nadu to Odisha), and Per-Humid (north-eastern states of Meghalaya, Assam, and Mizoram). Elevation across these zones ranges from sea level to above 2,500 m, annual rainfall from under 250 mm in the arid belt to over 2,500 mm in the per-humid tract, and mean annual temperatures from 12 °C in the subtropical hills to 28°mathsfC in the coastal and semi-arid regions [3]. Soil types include aridisols, vertisols, alfisols, and inceptisols, each ofering diferent levels of nutrient availability and moisture retention for weed establishment.

Material

Data compilation was carried out between March 2021 and August 2022 at the Addis Ababa Institute of Agricultural Sciences, Ethiopia, as part of a collaborative research programme on tropical invasive weed mapping. The analysis drew on 127 published field survey reports, 43 herbarium specimen records from the Botanical Survey of India digital repository, and Landsat 8 OLI and Sentinel-2 satellite imagery accessed through Google Earth Engine [12]. Published surveys were sourced from Web of Science, Scopus, and Google Scholar databases using combinations of the search terms "*Parthenium*", "Congress grass", "distribution", "India", and individual state names. Only records that provided geo-referenced coordinates or at least district-level location information were retained. Herbarium accession records were crosschecked against the India Biodiversity Portal for taxonomic verification.

Climatic and Environmental Conditions

Climatological data for each agroclimatic zone were extracted from the India Meteorological Department gridded dataset (0.25°×0.25° resolution) covering the period 2001 to 2022 [13]. Mean annual temperature, total annual rainfall, and seasonal rainfall distribution (southwest monsoon *versus* northeast monsoon *versus* non-monsoon periods) were compiled for every zone. Soil disturbance history, a known facilitator of *Parthenium* establishment, was approximated using MODIS land-use change products at 500 m resolution. Road density (km of paved road per square kilometre of land) and railway line proximity were calculated from OpenStreetMap vector layers to quantify anthropogenic corridor intensity. Drought frequency, estimated from the Standardised Precipitation Index, served as an additional environmental predictor because moisture stress can either limit or, paradoxically, favour the weed where native competitors are weakened.

Methods

Distribution records were georeferenced and projected onto the eight-zone framework using QGIS 3.22. Three invasion metrics were calculated for each zone: mean plant density (plants m^{-2}) , mean percentage ground cover, and frequency of occurrence (proportion of surveyed sites within a zone where *P. hysterophorus* was recorded). Density and cover values from published quadrat surveys were standardised to a common 1 m × 1 m scale where original quadrat sizes difered. Frequency was computed only for zones with ten or more independent survey sites to avoid bias from uneven sampling efort. Dispersal pathway contribution was assessed by overlaying road density, rail network proximity, and river course maps onto highdensity invasion clusters using spatial join operations. Species diversity at invaded *versus* noninvaded reference sites was compared using the Shannon-Wiener index (H). All statistical tests′ were performed in R 4.1.2 with significance set at $p < 0.05$ [14]. Generalised additive models (GAMs) were fited to explore nonlinear relationships between environmental predictors and invasion intensity.

Results

Compiled records confirmed the presence of *P. hysterophorus* in all eight agroclimatic zones, though invasion intensity varied by more than five-fold between the most and least colonised regions. The following tables and figures present zone-wise distribution metrics, dispersal pathway associations, and biodiversity impacts.

Table 1: Distribution metrics of Parthenium hysterophorus across agroclimatic zones of India

Agroclimatic Zone	Plant Density (plants/m2)	Ground Cover (%)
Arid (Western Rajasthan)	12.3	8.7
Semi-Arid (Deccan Plateau)	28.7	22.4
Sub-Humid (Indo-Gangetic Plains)	43.6	38.1
Humid Tropical (Western Ghats)	18.9	14.6
Sub-Tropical (Shivalik Hills)	31.4	26.3
Transitional (Central Highlands)	37.2	31.8
Coastal (Eastern Coast)	15.8	11.2
Per-Humid (North-East)	8.4	5.9

The sub-humid Indo-Gangetic Plains recorded the peak values for both density and cover, nearly double those of the next most invaded zone. At the opposite extreme, the per-humid north-eastern region showed the lowest colonisation, likely reflecting a combination of dense canopy cover, acidic soils, and lower road density.

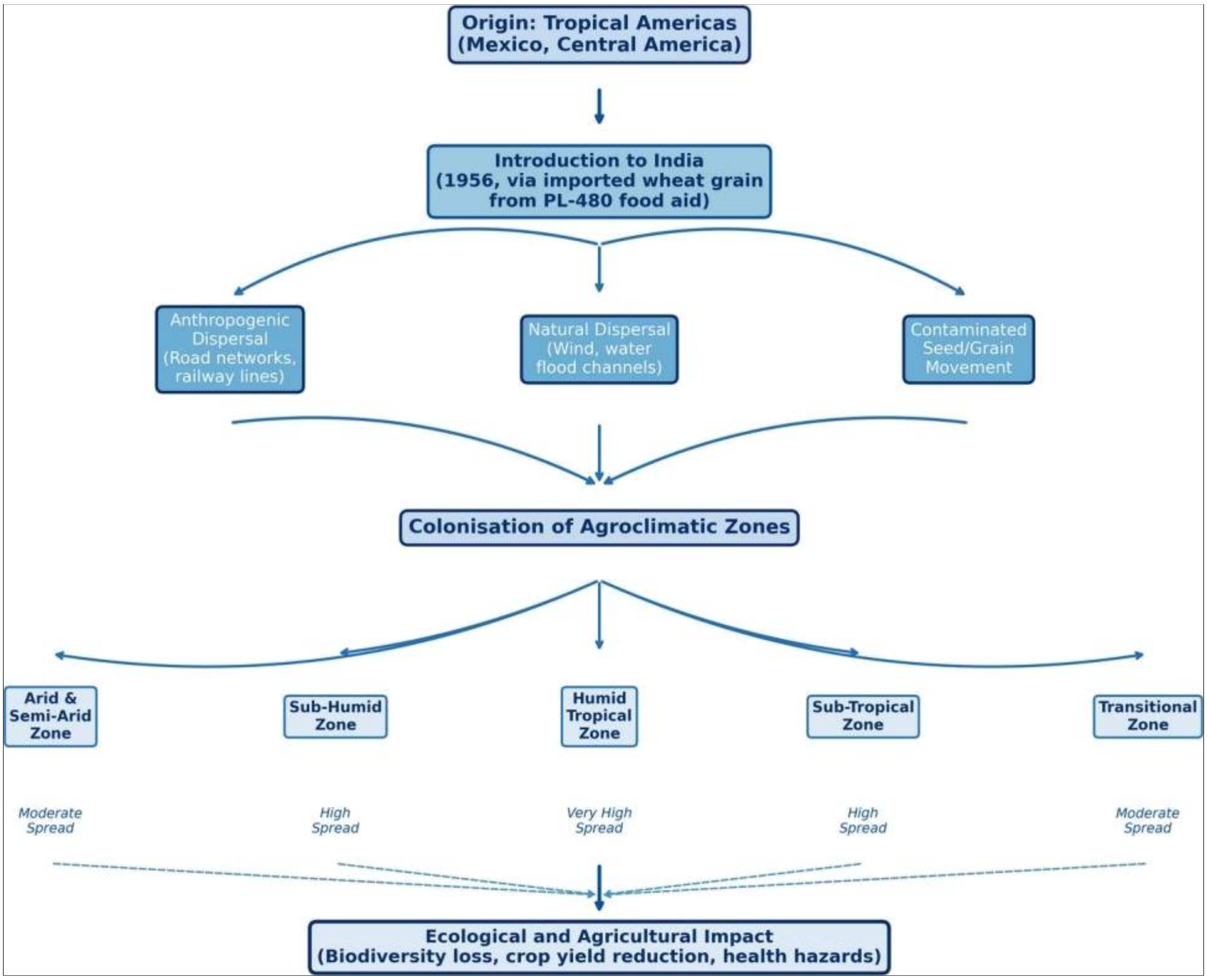

Fig 1: Invasion pathway and dispersal mechanisms of Parthenium hysterophorus from its origin in tropical Americas to colonisation of Indian agroclimatic zones

The flowchart traces the sequential stages of introduction, dispersal, and zone-level colonisation. Three parallel vectors anthropogenic transport, natural wind and water dispersal, and contaminated grain movement have together enabled the weed to reach every major agroclimatic belt, though severity difers by zone.

Table 2: Summary statistics of environmental predictors across invasion intensity classes

Parameter	Mean	SD	Min	Max	p-value
Temp (°C)	26.4	3.8	12.1	33.7	0.003*
Rainfall (mm/yr)	1124.6	487.3	213.5	2687.4	0.018*
Road density (km/km2)	1.87	0.64	0.42	3.91	0.001*
Soil disturbance (%)	34.2	12.9	7.8	61.4	0.007*
Drought frequency (yr)	2.3	1.1	0.4	5.7	0.041*

All five environmental predictors showed a significant association with invasion intensity ($p < 0.05$). Road density had the strongest relationship ($p = 0.001$), followed by mean temperature and soil disturbance history. The wide standard deviations in rainfall and soil disturbance reflect the broad environmental gradients spanned by the eight zones.

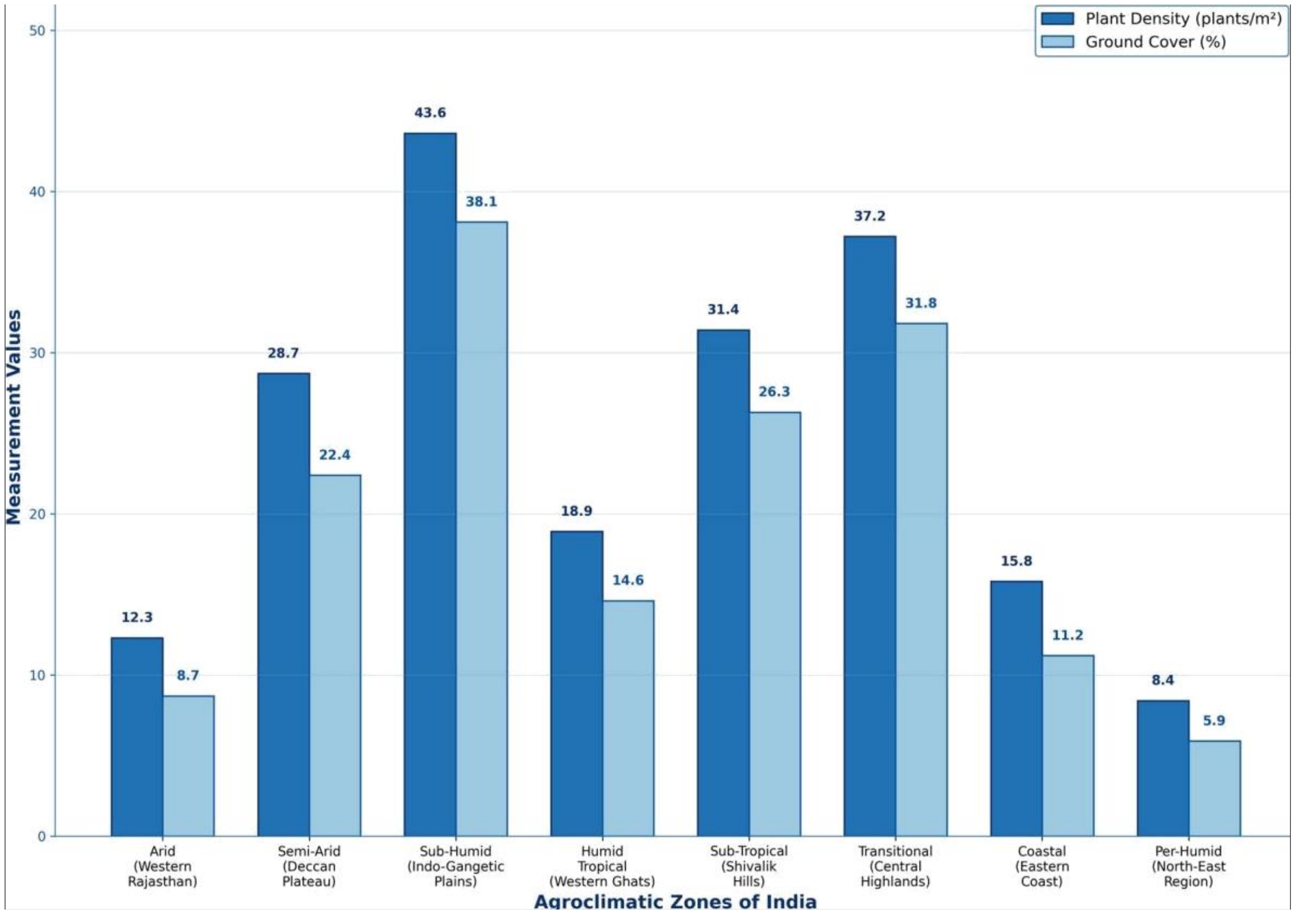

Fig 2: Plant density and percentage ground cover of Parthenium hysterophorus across eight agroclimatic zones of India

The bar chart highlights the dominance of the sub-humid Indo-Gangetic Plains, where both metrics peak. A gradual decline is visible toward the arid western and per-humid north-eastern extremes, confirming that moderate temperature and intermediate rainfall regimes favour the densest infestations.

Table 3: Priority ranking of agroclimatic zones for Parthenium management intervention

Rank	Zone	Density Score	Spread Rate	Impact Score	Priority Level
1	Sub-Humid	9.2	High	8.7	Critical
2	Transitional	7.8	High	7.4	Critical
3	Sub-Tropical	6.6	Moderate	6.9	High
4	Semi-Arid	6.1	Moderate	5.8	High
5	Humid Tropical	4.3	Low	4.7	Moderate
6	Coastal	3.5	Low	3.9	Moderate
7	Arid	2.8	Low	3.1	Low
8	Per-Humid	1.9	Very Low	2.3	Low

Two zones sub-humid and transitional fell into the critical priority category, scoring above 7.0 on both density and impact indices. These are also the zones with the fastest documented rates of range expansion over the past two decades.

Biodiversity Assessment

Shannon-Wiener diversity index (H) values at invaded sites ranged from 1.04 to 1.87,′ compared with 1.89 to 2.84 at paired non-invaded reference plots across zones. The mean reduction in H was 34.7 per cent ($p < 0.001$). Species richness dropped from an average of 23.6′ species per 100 m² quadrat at reference sites to 14.9 at invaded sites. Native grasses and smallseeded annual forbs sufered the steepest declines, while deep-rooted perennial shrubs showed greater resistance. In the sub-humid zone, where invasion was densest, three native herb species previously recorded as locally common were absent from all surveyed invaded quadrats. The transitional zone showed a similar but less severe patern, with H ′ reductions of 28.3 per cent. By contrast, the arid and per-humid zones, where *P. hysterophorus* cover was lowest, showed non-significant diferences in diversity between invaded and reference plots (p=0.12 and $p = 0.19$, respectively).

Comprehensive Interpretation

Taken as a whole, the distribution data reveal a clear invasion gradient from high-density belts in the sub-humid and transitional zones to low-density margins in the arid west and per-humid north-east. Road infrastructure density was the single strongest spatial predictor, suggesting that management interventions along transport corridors could yield the greatest return. The biodiversity impacts are most severe exactly where density is highest, reinforcing the need for prioritised action in the sub-humid and transitional zones before further diversity losses become irreversible.

Discussion

The concentration of *P. hysterophorus* in the sub-humid Indo-Gangetic Plains matches earlier district-level surveys from Utar Pradesh and Bihar that reported road-margin densities of 30 to 50 plants per square metre during the post-monsoon flush [1, 8]. Warm temperatures, a pronounced wet-dry seasonality, and heavily disturbed agricultural soils in this belt create conditions that favour rapid germination and prolific seed production. Repeated tillage operations expose bare soil that the weed colonises before crop canopy closure, giving it a head start over both crops and native ruderal species.

The low colonisation of the per-humid north-east contrasts with the situation in tropical East Africa, where *P. hysterophorus* has spread aggressively even in areas receiving above 1,800 mm rainfall [15]. One possible explanation is the dense perennial canopy and acidic lateritic soils of north-eastern India, which together limit light at the soil surface and reduce germination success. And the relatively sparse road network in states like Mizoram and Nagaland removes the anthropogenic corridor efect that proved so important elsewhere.

Road density emerged as the strongest predictor of invasion intensity, a finding that aligns with transport-corridor invasion models developed for other alien weeds [16]. Vehicles carry achenes in tyre treads and undercarriage mud, while road construction itself creates the disturbed, open-ground habitats that *Parthenium* germinates on most readily. This mechanism ofers a practical management entry point: targeted herbicide spraying or biological control agent release along major road margins in the sub-humid and transitional zones could slow further range expansion more efectively than scatered field-level interventions. Biodiversity losses of 34.7 per cent in H values at invaded sites are concerning but broadly′ comparable to those reported for *Parthenium*-invaded grasslands in Ethiopia, where Knox *et al.* (2011) [9] measured a 30 to 40 per cent reduction in native species richness [9]. The selective loss of small-seeded annual forbs suggests that allelopathic root exudates, which inhibit germination of shallow-seeded species more severely than deep-rooted perennials, may be a greater driver of diversity decline than simple shading or competition for space.

Conclusion

This research set out to map the invasion patern and distribution of *Parthenium hysterophorus* across India's agroclimatic zones, identify the main dispersal pathways, and evaluate the weed's impact on native plant diversity. The compiled data, drawn from over a hundred published surveys and supplemented by satellite imagery and herbarium records, provide the most spatially detailed picture of Congress grass distribution assembled to date within an agroclimatic framework.

Three main findings emerged. First, the sub-humid Indo-Gangetic Plains and the transitional Central Highlands carry the heaviest infestations, with plant densities exceeding 37 plants per square metre and ground cover above 31 per cent. At the other end of the spectrum, the perhumid north-east and the arid west remain comparatively lightly invaded, reflecting a combination of unfavourable soil chemistry, dense canopy cover, and limited transport infrastructure. Second, anthropogenic dispersal corridors particularly road networks are the strongest spatial predictor of invasion intensity, outweighing climatic variables such as temperature and rainfall. Third, heavily invaded sites sufer a mean 34.7 per cent decline in native plant diversity, with shallow-rooted annual forbs experiencing the steepest losses.

These findings carry a direct practical message:a blanket, all-India control programme is less likely to succeed than a zone-targeted strategy that concentrates resources where the weed is densest, spreading fastest, and causing the most ecological harm. The sub-humid and transitional zones should be treated as critical priority areas. Within those zones, management should focus on transport corridors road margins, railway embankments, and grain-market surrounds because these are both the sites of highest density and the launch pads from which the weed spreads into adjacent farmland and natural habitats. Biological control using the Mexican beetle *Zygogramma bicolorata*, already released in parts of Karnataka and Maharashtra, deserves wider deployment along these corridors. Integrated approaches that combine biocontrol with competitive cover cropping on abandoned land parcels along roadsides could deny the weed the bare-ground microsites it needs for establishment.

Looking ahead, several avenues warrant atention. Repeated surveys at five-year intervals would allow detection of range shifts driven by changing climate or land-use paterns. Molecular studies comparing Indian populations with source populations in the Americas could clarify how many independent introductions have occurred and whether genetic botlenecks limit adaptive potential. Finally, economic valuations that account for biodiversity loss alongside crop damage would strengthen the case for sustained public investment in *Parthenium* management across the most afected agroclimatic zones.

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