East African Journal of Health and Science
eajhs.eanso.org
Volume 8 Issue 2, 2025
Print ISSN: 2707-3912 | Online ISSN: 2707-3920
Title DOI: https://doi.org/10.37284/2707-3920

EANSO
EAST AFRICAN NATURE & SCIENCE ORGANIZATION

Original Article

Diversity, Patterns of Distribution, and Bayesian Projected Trends of the Ecological Impact of Invasive Alien Plant Species in the Mount Cameroon Region

Dr. Ndam Lawrence Monah, PhD[1], Aba Sihvanus Lenyuy[1], Juru Nzegong Victor[1], Dr. Awo Miranda Egbe, PhD[1], Toumguem Fotso Ornella[1], Dr. Njilar Rita Mungfu, PhD[1] & Prof. Fonge Beatrice Ambo, PhD[1]*

[1] University of Buea, P. O. Box 63, Buea, Cameroon.
*Author for Correspondence ORCID ID; https://orcid.org/0000-0002-5201-3538; Email: lawrencendam3@gmail.com

Article DOI: https://doi.org/10.37284/eajhs.8.2.3362

Date Published:

21 July 2025

Keywords:

Invasive Alien Species, Biodiversity, Spatial Distribution, Bayesian Modelling, Ecological Impact, Mount Cameroon, Habitat Disturbance.

ABSTRACT

Invasive alien plant species (IAS) are a major threat to biodiversity, ecosystem function, and sustainable land use, especially in tropical hotspots like the Mount Cameroon region. Despite its ecological significance, comprehensive data on the diversity, distribution, and projected impacts of IAS in this region have been lacking. This study systematically inventoried IAS, analysed their spatial and habitat distributions, assessed their effects on native plant communities, and modelled future expansion trends. Between September 2019 and November 2021, a field survey was conducted across 120 permanent plots (1,000 m² each) in four representative sites—Buea, Bakingili, Limbe, and Idenau-covering roadsides, farmlands, and forests. Species identification, cover estimation, and habitat characterisation followed standardised protocols. Diversity indices (Shannon-Wiener, evenness, richness, Sørensen similarity) were calculated for invaded and uninvaded plots. GIS mapping and Bayesian hierarchical modeling were employed to assess spatial patterns, environmental drivers, and project IAS expansion from 2020 to 2030. A total of 25 IAS from 16 families and 24 genera were identified, with Asteraceae and Poaceae being most salient. Annual herbs constituted 70% of the IAS flora. Species richness and evenness were highest in Buea (H'=2.57, S=17, E=0.91) and lowest in Bakingili. Roadsides and farmlands exhibited significantly higher IAS abundance than forests ($p=0.036$). Bayesian projections indicated a progressive expansion of IAS, with Chromolaena odorata, Tithonia diversifolia, and Eleusine indica expected to be the most aggressive invaders, and the cumulative IAS-occupied area projected to exceed 75,000 m² by 2030. Invaded sites showed marked declines in native species diversity and evenness. These findings highlight the urgent need for targeted, site-specific management interventions, particularly along roadsides and for rapidly expanding species. Integrating field inventories, GIS, and Bayesian modeling provides robust insights for prioritising eradication and control strategies to mitigate the ecological and economic impacts of IAS in the Mount Cameroon region**.**

APA CITATION

Monah, N. L., Lenyuy, A. S., Victor, J. N., Egbe, A. M., Ornella, T. F., Mungfu, N. R. & Ambo, F. B. (2025). Diversity, Patterns of Distribution, and Bayesian Projected Trends of the Ecological Impact of Invasive Alien Plant Species in the Mount Cameroon Region. *East African Journal of Health and Science*, *8*(2), 166-191. https://doi.org/10.37284/eajhs.8.2.3362

CHICAGO CITATION

Monah, Ndam Lawrence, Aba Sihvanus Lenyuy, Juru Nzegong Victor, Awo Miranda Egbe, Toumguem Fotso Ornella, Njilar Rita Mungfu and Fonge Beatrice Ambo. 2025. "Diversity, Patterns of Distribution, and Bayesian Projected Trends of the Ecological Impact of Invasive Alien Plant Species in the Mount Cameroon Region". *East African Journal of Health and Science* 8 (2), 166-191. https://doi.org/10.37284/eajhs.8.2.3362

HARVARD CITATION

Monah, N. L., Lenyuy, A. S., Victor, J. N., Egbe, A. M., Ornella, T. F., Mungfu, N. R. & Ambo, F. B. (2025). "Diversity, Patterns of Distribution, and Bayesian Projected Trends of the Ecological Impact of Invasive Alien Plant Species in the Mount Cameroon Region", *East African Journal of Health and Science*, 8(2), pp. 166-191. doi: 10.37284/eajhs.8.2.3362

IEEE CITATION

N. L., Monah, A. S., Lenyuy, J. N., Victor, A. M., Egbe, T. F., Ornella, N. R., Mungfu & F. B., Ambo "Diversity, Patterns of Distribution, and Bayesian Projected Trends of the Ecological Impact of Invasive Alien Plant Species in the Mount Cameroon Region", *EAJHS*, vol. 8, no. 2, pp. 166-191, Jul. 2025.

MLA CITATION

Monah, Ndam Lawrence, Aba Sihvanus Lenyuy, Juru Nzegong Victor, Awo Miranda Egbe, Toumguem Fotso Ornella, Njilar Rita Mungfu & Fonge Beatrice Ambo. "Diversity, Patterns of Distribution, and Bayesian Projected Trends of the Ecological Impact of Invasive Alien Plant Species in the Mount Cameroon Region". *East African Journal of Health and Science*, Vol. 8, no. 2, Jul. 2025, pp. 166-191, doi:10.37284/eajhs.8.2.3362.

INTRODUCTION

Invasive alien species (IAS) are organisms introduced to environments outside their native range, often through human activities such as trade, agriculture, and horticulture, and have the potential to cause significant harm to new ecosystems (Richardson et al., 2000; Mack et al., 2000). The globalisation of trade and travel has accelerated their spread, with the horticultural market playing a notable role in their establishment in new areas (Hulme, 2009). IAS are widely recognised as the second most significant threat to biodiversity after habitat loss, driven by anthropogenic forces such as over-exploitation, urbanisation, industrialisation, environmental pollution, land-use change, and climate change (Bellard et al., 2018; Ljubojević et al., 2022). These non-native organisms can disrupt native biodiversity, degrade ecosystem services, reduce environmental quality, and inflict substantial economic costs, as well as threaten human health and food security, thereby undermining sustainable development goals (Ljubojević et al., 2022; Cheng et al., 2023).

IAS, particularly invasive alien plant species (IAPS), exhibit remarkable adaptability to diverse environmental conditions and often thrive in disturbed habitats, facilitated by both natural and anthropogenic factors, including climate change (Burgiel & Muir, 2010; Kariyawasam et al., 2019). Their ability to outcompete native species for resources, alter soil chemistry, and modify ecosystem processes such as nutrient cycling and carbon sequestration has been well documented (Kenfack, 2017; Juru et al., 2024). For example, species like *Chromolaena odorata* have been shown to impact soil properties and microbial communities in the Mount Cameroon region, leading to cascading effects on ecosystem function (Juru et al., 2024). The ecological impacts of IAPS extend to reducing local species diversity, facilitating habitat degradation, and increasing the vulnerability of native species to extinction (Hejda et al., 2009; Kenfack, 2017).

Understanding the mechanisms underlying biological invasions is complex, with several theories proposed, such as the enemy release hypothesis, novel weapons hypothesis, empty niche hypothesis, and evolution of increased competitive ability hypothesis (Groves et al., 2005). However, the success of plant invasions is generally attributed to a combination of these factors rather than a single cause (Inderjit et al., 2018). Consequently, the management and control of IAS have become primary focuses in restoration ecology, with particular emphasis on compiling comprehensive inventories and understanding the spatial distribution and spread of these species (Witt et al., 2018; Ansong et al., 2019).

Large-scale observations combined with predictive models have been instrumental in identifying invasion risk areas and understanding the drivers and consequences of local biodiversity impacts (Oh et al., 2021). Species Distribution Models (SDMs) and advanced statistical approaches, such as Bayesian spatial models, have been increasingly applied to forecast the occurrence and evolution of IAS (Warton et al., 2015; Abrego et al., 2017; Da Re et al., 2019). Bayesian models are particularly valuable as they allow for the integration of prior knowledge, the incorporation of spatial autocorrelation and environmental covariates, and the quantification of uncertainty in predictions, leading to more robust and reliable projections (Stanaway et al., 2011; Gelman et al., 2014). These probabilistic projections are essential for informing management strategies, prioritising control efforts, and supporting decision-making in conservation (Keenan et al., 2018; Nsashiyi et al., 2022).

The Mount Cameroon region, located in Southwest Cameroon, is a biodiversity hotspot with a rich array of flora and fauna, including a high number of endemic and introduced plant species (Kenfack, 2017; Chuyong et al., 2019). However, it is increasingly threatened by invasive alien plant species, which are facilitated by rapid urbanisation, infrastructural expansion, tourism, and other anthropogenic activities that create ecological gaps for potential invasion (Juru et al., 2024). Despite its ecological importance, there is currently no comprehensive baseline inventory of invasive alien plant species for the Mount Cameroon region, and gaps remain in understanding their ecological impacts and distribution patterns (Fonge et al., 2013). This lack of information poses significant challenges to effective management, as invasive species continue to alter ecosystems, threaten biodiversity, and increase agricultural and economic costs (Kenfack, 2017; Nkuinkeu et al., 2023).

Given the region’s vulnerability and the urgent need for targeted management, a comprehensive inventory of IAS in the Mount Cameroon region, coupled with analyses of temporal trends and predictive modelling, is critical for identifying priority responses and enhancing our understanding of plant invasions (Da Re et al., 2019). Localised studies and tailored management approaches are essential to address the unique challenges posed by invasive plants in different ecological contexts. Therefore, the present study aimed to assess the diversity, distribution patterns, and ecological impact of invasive alien plant species in the Mount Cameroon region, utilising field observations and Bayesian modeling to inform effective conservation and management strategies.

METHODS

Study Area

The study was carried out in the Mount Cameroon Region, situated along the coastal belt of the Gulf of Guinea in Central Africa, specifically within the South West Region of Cameroon. Geographically, the region is positioned between latitudes 3° 57' and 4° 28' N and longitudes 8° 58' and 9° 24' E. It covers an area of approximately 2,700 km², encompassing the main massif, which alone accounts for about 1,500 km². Mount Cameroon itself rises to an elevation of 4,095 meters above sea level (m.a.s.l.), making it the highest peak in West and Central Africa. Mount Cameroon exerts a profound influence on the local climate, creating a range of microclimates across its slopes. The region is renowned for its exceptionally high rainfall, particularly on the windward western slopes, where mean annual precipitation can reach up to 10,000 mm in Debundscha, one of the wettest places on earth. This rainfall gradually decreases eastward, falling to less than 2,000 mm annually in the rain-shadow areas. Temperature variation is also notable: the western slopes experience a broader range (24–28°C), while the eastern slopes are slightly warmer and more stable (27–28°C) (Cable and Cheek, 1998). Relative humidity in the Mount Cameroon region is generally high throughout the year, averaging about 90% annually. Both rainfall and relative humidity tend to decrease with increasing altitude, alongside a corresponding drop in temperature. The mountain's volcanic origin has endowed it with fertile soils, making most areas highly suitable for agriculture, except for zones affected by lava flows where soils are less developed and mineral-rich (Tening et al., 2013). The region's vegetation exhibits distinct altitudinal zonation, with significant ecological discontinuities observed at elevations of approximately 800, 1,500, 2,300, 3,000, and 4,000 meters. Forests dominate up to around 2,000 m a.s.l., above which they give way to montane savanna and grassland communities (Cable & Cheek, 1998).

Field Survey Design and Data Collection of Invasive Alien Species Diversity

Prior to data collection, verbal informed consent was obtained from all concerned communities after clearly explaining the objectives and relevance of the study. Participation was fully voluntary, and each community retained the right to withdraw at any time. All field activities were conducted in accordance with ethical research standards. Ethical approval and research clearance for this study were granted by the Faculty of Science Ethical Review Board, University of Buea.

A comprehensive field survey was conducted in the Mount Cameroon region from September 2019 to November 2021, targeting the peak detection of invasive alien species (IAS) across diverse seasonal conditions. Four strategically chosen sites—Buea, Bakingili, Limbe, and Idenau-were selected to represent the region's ecological and anthropogenic heterogeneity. Site selection criteria included accessibility, intensity of anthropogenic disturbance, touristic relevance, historical context, and safety considerations. Within each site, three principal land use types (roadsides, farmlands, and forest areas) were systematically surveyed. The Modified Whittaker sampling protocol (Stohlgren et al., 1995) was employed, enabling robust, multi-scale assessment of plant community composition and IAS abundance. A total of 120 permanent plots (10 per land use type, 30 per site) were established, each measuring either 20 × 50 m or 25 × 40 m (1,000 m^2) to account for local topographical variation. Each main plot contained a nested structure: ten 0.5 × 2 m (1 m^2) subplots systematically spaced along the interior border, two 2 × 5 m (10 m^2) subplots in alternate corners, and a central 5 × 20 m (100 m^2) subplot.

All vascular plant species within each quadrat were identified in situ using diagnostic morphological characteristics. When field identification was inconclusive, specimens were collected following standard botanical protocols and subsequently identified at the Limbe Botanic Garden Herbarium. Additional direct observations were made to document habitat specificity and microhabitat diversity. Inter-plot distances ranged from 500 to 1,000 m, reflecting landscape and land use heterogeneity. The IAS cover abundance was estimated using the Braun-Blanquet (1965) scale (Wittenberg et al., 2004). Species exhibiting >5% cover were classified as invasive; those below this threshold were excluded from subsequent analyses. All putative IAS were cross-referenced with authoritative floras—including the Flora of Cameroon, Flora of West Africa, Flora of Assam, and World Flora Online—and validated against published literature (Bhatta et al., 2020; Rai et al., 2022) to confirm their alien status in the Mount Cameroon region. Taxonomic classification followed the Angiosperm Phylogenetic Group (APG) III system.

Phytogeographical attributes-such as mode of propagation, dispersal mechanism, and pollination type-were systematically recorded. Each species was further categorised by growth form (herb, shrub, or tree), and comprehensive inventories were compiled, detailing botanical name, family, common name, nativity, and growth form, as per Khuroo et al. (2007). All inventory data were digitised using Microsoft Excel (2013) and analysed in R, a statistical computing environment. Descriptive statistics were applied, and qualitative results were visualised graphically. Species relative abundance was calculated as the proportion of individuals of each species relative to the total number of individuals recorded.

Distributional Patterns of Dominant Invasive Alien Plant Species

The spatial distribution of dominant invasive alien plant species (IAS) across the Mount Cameroon region was systematically mapped using Geographic Information System (GIS) technology, specifically Quantum GIS (QGIS). During field surveys, precise georeferencing was achieved by recording the coordinates of each IAS-infested quadrat using a handheld Global Positioning System (GPS) device. Sampling intervals ranged from 500 meters to 1 kilometre, ensuring comprehensive spatial coverage across all four focal sites: Buea, Bakingili, Limbe, and Idenau.

To enhance the completeness of the dataset, opportunistic observations were also made in ecologically sensitive microhabitats such as stream banks and shorelines, particularly for species that were absent from the immediately preceding plots. This approach maximises the detection and documentation of IAS occurrences throughout the landscape. All GPS data were initially recorded in Degrees Minutes (DM) format, subsequently converted to decimal degrees, and organised in Microsoft Excel (2013). The processed coordinates were then exported as comma-separated values (CSV) and imported into QGIS for spatial analysis. Within QGIS, shape files representing point, line, and polygon features were generated to accurately depict the distribution of IAS and relevant geographic features, including roads, settlements, vegetation types, topography, and hydrological elements. Final distribution maps were created using the QGIS Print Composer, which allowed for the integration of essential cartographic elements such as coordinate grids, scale bars, cardinal directions, and legends. These high-resolution maps were exported in both PDF and JPEG formats, providing robust visualisations to support further ecological analysis and management planning. This GIS-based approach enabled a rigorous and spatially explicit assessment of IAS distribution, facilitating the identification of invasion hotspots and informing targeted management interventions.

Ecological Impacts: Invasive Alien Species Coverage and Projections

The ecological impact of invasive alien plant species (IAS) on native plant communities was assessed using the approach described by Hejda et al. (2009). From the permanent plots established via the modified Whittaker sampling method, 24 plots were selected-two per land use type across six study sites—where IAS presence was confirmed. Within each selected plot, two pairs of nested subplots (5 m × 5 m) were established: one pair in areas dominated by IAS (invaded plots, characterised by monoculture stands), and the other in adjacent, uninvaded vegetation with similar site conditions for accurate comparison. In each subplot pair, all plant species were recorded, and their percentage cover was estimated at three time points (2019, 2020, and 2021). These data were used to calculate key diversity metrics for both invaded and uninvaded plots, including the Shannon diversity index (H′), evenness (E), species richness, and Sørensen similarity index (S). The mean values for each index were computed per plot and site, and differences in these indices served as quantitative measures of IAS impact on native species composition and diversity. The data were entered into Microsoft Excel (version 23). The pooled data were exported into SPSS version 13.0 and subjected to ANOVA. Their diversity indices were also computed and analysed using equations 1, 2, 3, and 4. Means were separated using the Kruskal-Wallis test. The differences in means were considered significant at P<0.05.

The specific equations used for each index were**:**

$$Shannon\ H' = \sum_{i}^{i=1} pilnpi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where: H' = Index of species diversity, Pi = Proportion of total sample belonging to i

pi = Number of species.

$$Evenness = \frac{H}{Hmax} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Where H = Shannon index, Hmax = ln (number of species)

$$Sorenson\ index, Cn = \frac{2C}{A+B} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

Relative Frequency = (No of a species / Total number of species) × 100 ……………..... (4)

Where: C_n = Sorensen's similarity coefficient, A and B are the number of individuals per site, and C = number of species common to both sites.

Furthermore, the displacement of native species was predicted by IAS expansion over time, with an emphasis on the spread and intensity of mono-specific stands of IAS. All plots established and sampled in 2019 were resampled in 2020 and 2021 once yearly. The percentage frequencies and the area covered by IAS were calculated relative to the area sampled in each of the four selected sites. The three-point data (3 years of studies) were exploited by using a Bayesian predictive model to generate a graphical count of the IAS per species for each area and to predict the annual IAS counts over time for the next 10 years as described below.

Data Sources: Two sources of data were used, including field time-series data on the area occupied by Invasive Alien Species (IAS) and IAS counts per area collected at the study sites for three years (2019–2021); and weather data for 2019–2021 downloaded from the NASA POWER platform for the corresponding geographic coordinates of the study areas. This analysis is limited to the data for Buea and Limbe, as NASA POWER data are unavailable for the other locations.

Variables: Dependent variable equals the area of IAS coverage in square meters (m^2) measured as average per year and study site. Independent variables include: IAS species-specific count per m^2; IAS species-specific area (%); IAS species-specific GPS location (latitude and longitude); IAS area per m^2; native species area per m^2; study site; and year. Each study site covered 500 m^2. Additionally, climate determinants comprise temperature at 2 m (°C), specific humidity at 2 meters (g/kg), wind speed at 2 meters (m/s), profile soil moisture (%), precipitation (mm/day), and year of observation. Variable selection was based on the literature (Mainali et al., 2015) and the test statistic from simple linear regression and the Pearson test for correlation ($p < 0.05$).

Statistical Analysis: To examine the factors influencing the area covered by IAS, we utilised a Bayesian hierarchical model. This modelling approach is particularly advantageous for ecological data, as it allows for the incorporation of both fixed and random effects, thereby providing a more nuanced understanding of the relationships among variables. (Gelman et al., 2020). Incorporating several independent variables that are hypothesised to affect the area of IAS coverage, the model can be expressed with the following equation;

$$\begin{aligned} ln(A_{m^2})_{it} = \beta_0 &+ \beta_1 D_{it} + \beta_2 O_{it} + \beta_3 (G \cdot N)_{it} \\ &+ \beta_4 (T \cdot H)_{it} + \beta_5 (H \cdot W)_{it} \\ &+ \beta_6 (T \cdot S)_{it} + \beta_7 (H \cdot P)_{it} \\ &+ \beta_8 (S \cdot P)_{it} \\ &+ \sum\nolimits_{j=1}^{k} \gamma_j (ias\_specie \cdot C)_{it} \\ &+ \sum\nolimits_{m=1}^{p} \theta_m S_{it} + \sum\nolimits_{n=1}^{p} \delta_n Y_{it} \\ &+ \mu_i + \epsilon_{it} \end{aligned}$$

Whre: $ln(A_{m^2})_{it}$ is the natural logarithm of the area coverage of IAS for observation i at time t. β_0 is the intercept term. β_1 is the coefficient for species-specific area D. β_2 is the coefficient for spatial lag variable O, which represents the average value of the dependent variable (IAS area) for neighbouring observations based on species-specific latitude and longitude positions. β_3 is the coefficient for the interactions between IAS area G and native species area N. Coefficients β_4, β_5, β_6, and β_8 represent the effect of the interactions between temperature T and humidity H, H and wind speed W, T and soil moisture S, H and precipitation P, S and P, respectively. $\sum_{j=1}^{k} \gamma_j$ captures the variation in count C across species (ias_specie). Each γ_j is a coefficient associated with the interaction between C and the j-th ias_specie, and summation $\sum_{j=1}^{k}$ indicating that all k categories of ias_specie. θ_m is the coefficient associated with the m-th study site S relative, with summation $\sum_{m=1}^{p}$ considering all p study sites included. δ_n is the coefficient associated with the n-th year Y relative to a baseline year, with summation $\sum_{n=1}^{p}$ considering all p years included. μ_i shows random effects associated with all grouped factors. ϵ_{it} is the error term.

The priors for parameters were specified as follows: main effects and interaction terms, normal priors with mean 0 and standard deviation 100 [$\beta \sim N(0, 100)$]; variance component, inverse gamma prior $\sum_1 \sim igamma(0.01, 0.01)$. This specification of weakly informative priors allows the data to significantly influence the posterior distributions while still embedding some prior beliefs about the parameters (Gelman et al., 2020).

The setting of the interaction terms was guided by the literature (Mainali et al., 2015) and also by model diagnostics. These were defined as random effects to account for variability that might not be captured by the fixed effects (Gelman et al., 2020). Standard diagnostics to verify the convergence of the Markov Chain Monte Carlo (MCMC) covered visual observations of trace plots for overlap of chains, as well as the Gelman-Rubin diagnostics for values close to 1 and at most less than 1.1 (Gelman & Rubin, 1992).

For a case study of projections, we employed a standard regression forecasting approach, proceeding in two steps. In step one, the relationship between the dependent and independent variables was established by estimating the β vectors (Chi et al., 2011). The time variable corresponds with the study year. Y (2019), $Y + 2$ (2020) and $Y + 3$ (2021). In step two, out-of-sample IAS area predictions for years 2020 to 2030 that represent the periods between $t + 2$ to $t + 21$, derived based on the relationships established in step one. Also, out-of-sample estimates of each dependent variable were constant per the average of the estimates of the three survey years.

RESULTS

Taxonomic Inventory and Diversity Patterns of Invasive Alien Species in the Mount Cameroon Region

This study presents the first comprehensive taxonomic inventory of invasive alien plant species (IAS) in the Mount Cameroon region, resulting in the identification of 25 IAS spanning 16 families and 24 genera (Table 1; Figure 1). The families Asteraceae and Poaceae were the most represented, reflecting global trends in plant invasions. Site-Specific Family and Species Richness (2a).

Table 1: Invasive Alien Species Recorded in the Mount Cameroon Region

Species	Common name	Origin	Reference of Origin	Growth form
Ageratum conyzoides L	White weed	South America	Kosaka et al. (2010)	Annual herb
Bidens pilosa L	Black jack	South America	Kosaka et al. (2010)	Annual herb
Chromoleana odorata (L) R. King and H. Robinson	Achacasala		Kosaka et al. (2010)	Perennial herb
Tithonia diversifolia (Hemsly) A. Gray	Sun flower	South Africa Central America	Oludare and Muoghalu (2014)	Perennial shrub
Cecropia peltata L	Trumpet tree	South America	Binggeli (2005)	Perennial tree
Commelina capitata (Benth)	Unknown	Europe	Orni et al. (2018)	Annual herb
Phyllanthus amarus Schumach	Unknown	North America	Pysek et al. (2017)	Annual herb
Sida acuta Burm.F	Broom weed	North America	Debnath et al (2015)	Annual shrub
Oxalis corymbosa L	Pink grass	South America	Srivastava et al. (2014)	Annual herb
Lantana camara L	Colour flower	South America	Kosaka et al. (2010)	Perennial herb

Distinct patterns of family richness and composition were observed across the four surveyed sites. Buea hosted 10 IAS families, with Asteraceae being most prevalent and Polygonaceae least represented. Oxalidaceae and Polygonaceae were unique to this site. Idenau recorded 11 families, again dominated by Asteraceae, with Oxalidaceae least abundant. Cleomaceae and Pteridaceae were unique to Idenau. Limbe contained 9 families, including two unique families (Fabaceae and Meliaceae); Asteraceae was most abundant, and Meliaceae was least abundant. Bakingili had a lower diversity, with only three families (Asteraceae, Urticaceae, and Poaceae), none unique to the site. Across all sites, IAS were represented in at least one of three major growth forms: trees, shrubs, and herbs. Annual herbs constituted the majority (12 species, 70%), while perennial shrubs were the least represented (Fig. 3b).

Habitat Distribution and Biogeographic Origin

Invasive species were detected in all three principal land uses—roadsides, farmlands, and forests (Fig. 4c). Biogeographically, most IAS originated from Asia (four species), Europe (four species), and North America (three species). Only a minority were native to West, South, or East Africa (one species each; Fig. 5d).

However, the frequency of IAS was highest along roadsides in Limbe (47%), Idenau (56%), and Buea (55%), and lowest in forests, except for Bakingili, which exhibited equal IAS occurrence across all habitats (32%) (Fig. 7). This pattern underscores the role of anthropogenic disturbance and edge effects in facilitating invasions).

Abundance Patterns and Statistical Analyses

IAS abundance varied significantly across sites (Kruskal-Wallis, $p = 0.00017$), with Buea exhibiting the highest and Bakingili the lowest overall abundance. Post-hoc Wilcoxon tests revealed that IAS abundance in Buea was significantly higher than in Bakingili (p = 2.2e-05), Idenau (p = 0.033), and Limbe (p = 0.024). Limbe also had significantly higher IAS abundance than Bakingili (p = 0.0088), while no significant difference was observed between Limbe and Idenau (p = 0.74). Idenau, however, had significantly greater IAS abundance than Bakingili (p = 0.0055) (Fig. 7). In Limbe, Centrosema pubescens was identified as the most abundant IAS.

Habitat type exerted a significant influence on IAS distribution (Kruskal-Wallis, p = 0.036). The number of IAS was consistently highest along roads and lowest in forests. While the difference in IAS abundance between roads and farms was not statistically significant (Wilcoxon, p = 0.77), both habitats supported significantly higher IAS abundance than forests (Wilcoxon, p = 0.042; Fig. 8).

Figure 1: *Achyranthes aspera* var (A), *Ageratum conyzoides* L. (B), *Cecropia peltata* L. (C), *Chromolaena odorata* L. (D), *Oxalis corymbosa* L. (E), *Phyllanthus amarus* Shumach (F), *Bambusa vulgaris* Schrad. (G) *Mimosa pudica* L. (H), *Bidens Pilosa* (I), *Commelina sp Benth* (J), *Sida acuta* Burm(K), *Amaranthus spinosus* (L), *Lantana camara* L (M), Commelina capitata Benth (N), *Cyperus fertilis* Bleck (O), *Persicaria hydropiper* L. Delarbre (P), *Pteridium aquilinum* (L.) Kuhn (Q), *Tithonia diversifolia* Hemsly (A.Gray) (R), *Eleusine indica* (L) Gaertn (S), *Centrosema pubescens* Benth. (T), Megathyrsus maximus Bruce (U), Carapa procera A, Chev (V), Setaria megaphylla (Steud) T.Dur and Chinz. (W), *Penniseteum purpureum.* (X), *Cleome ciliata* (Shum & Thonn) (Y)

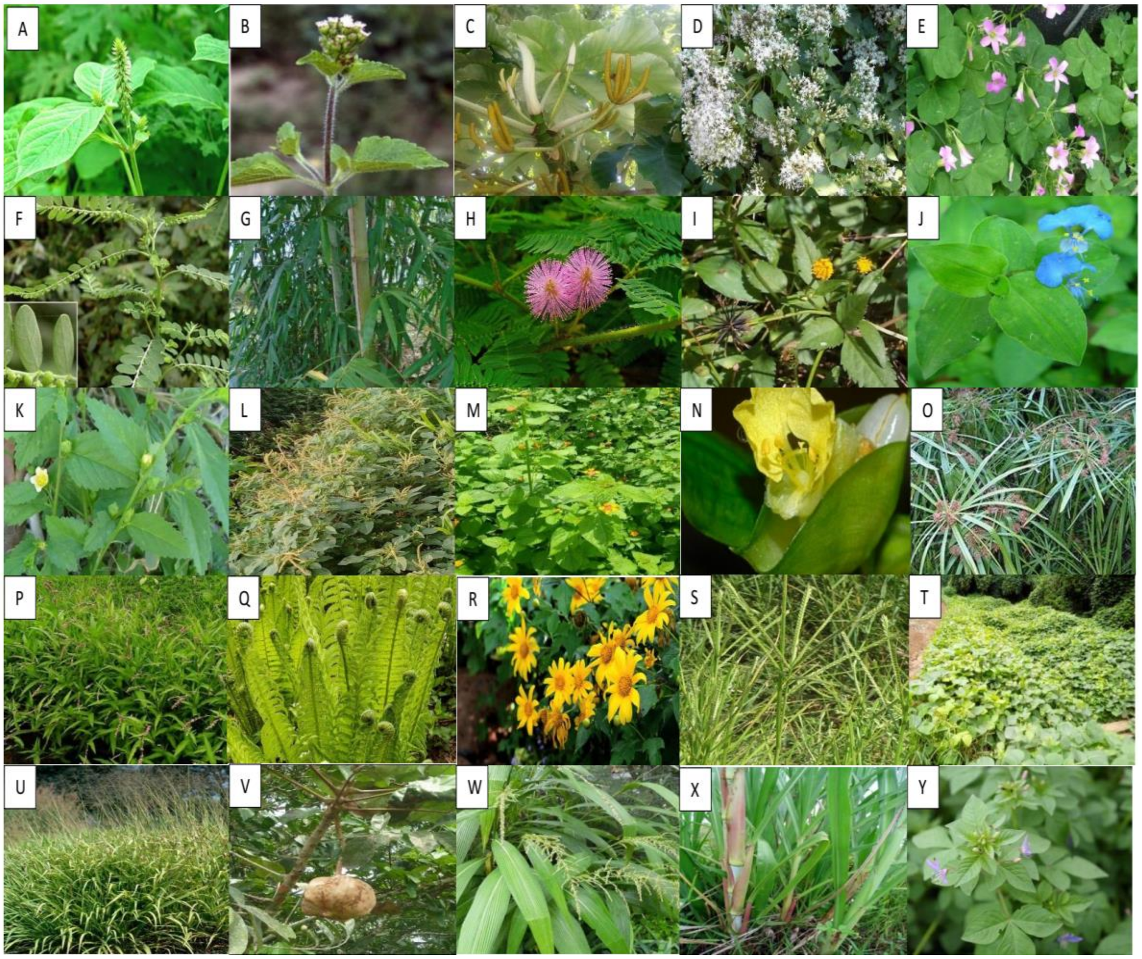


Figure 2: Diversity of IAS Plant Families Across Habitats (a)

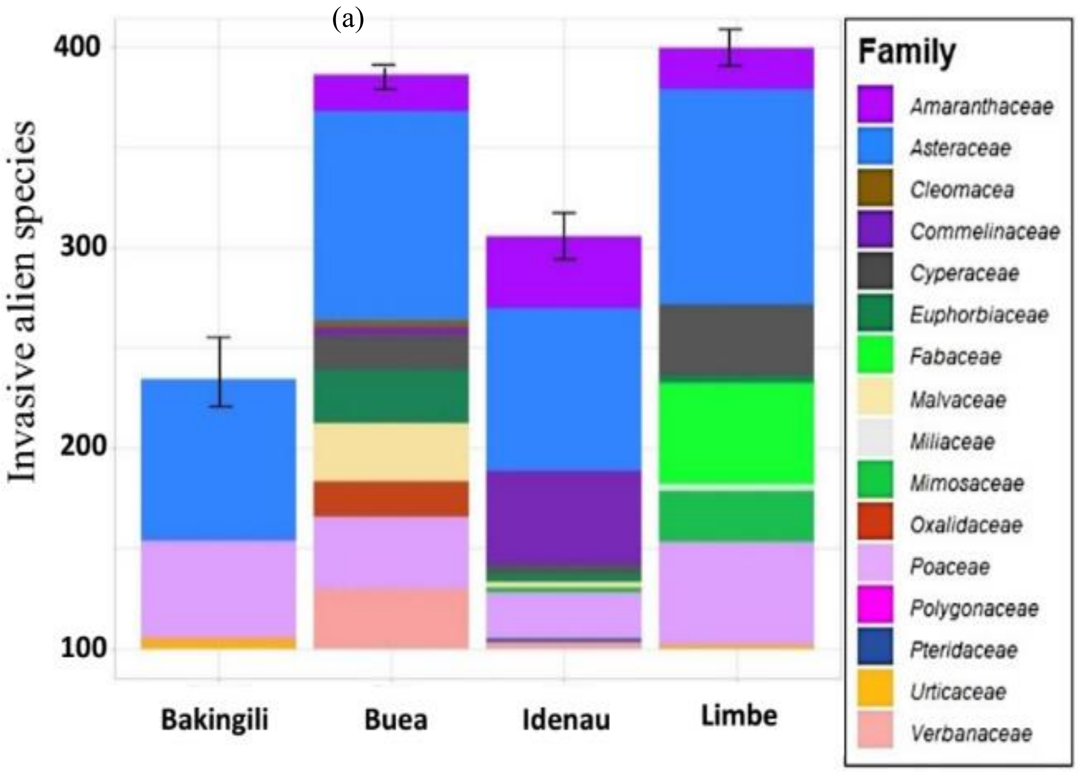


Figure 3: According to Growth Form (B)

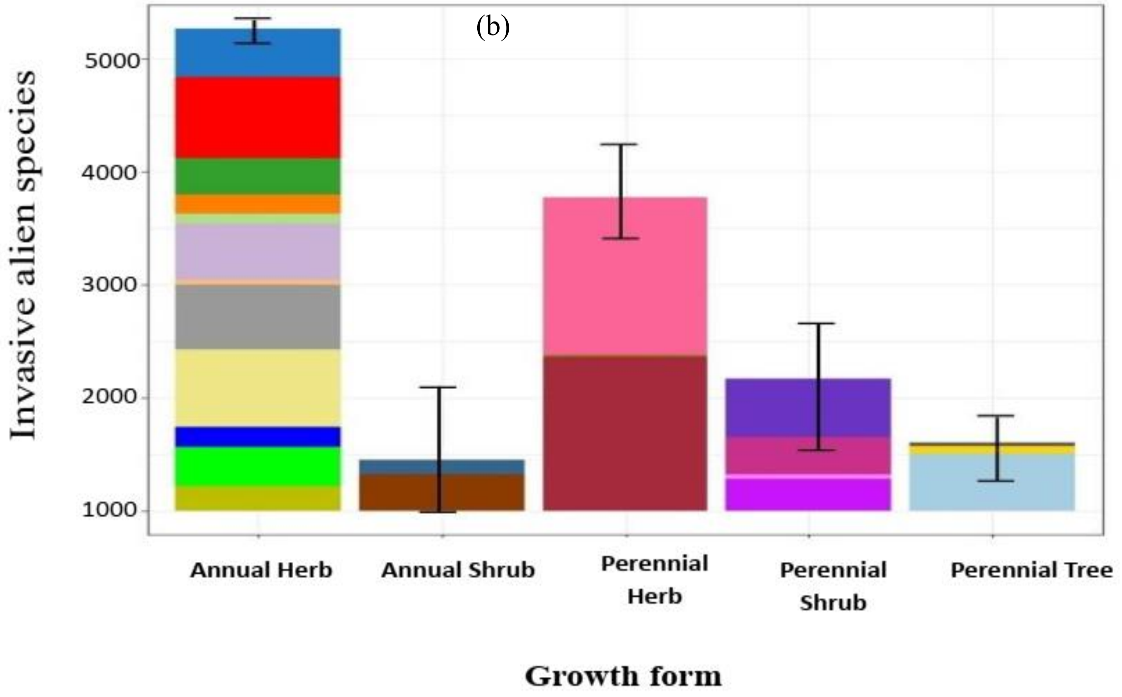


Figure 4: Across Land Uses (C)

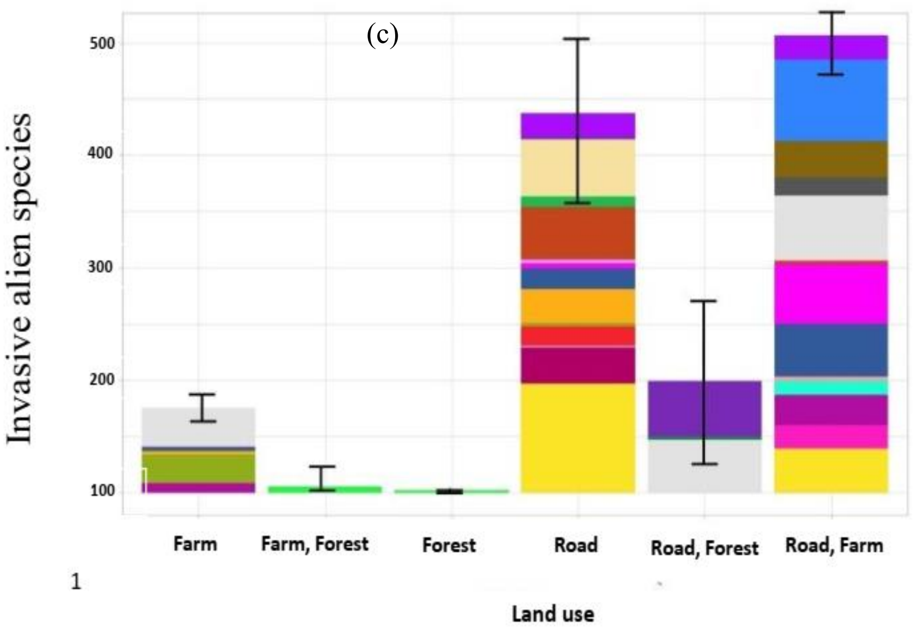


Figure 5: According to Nativity (D)

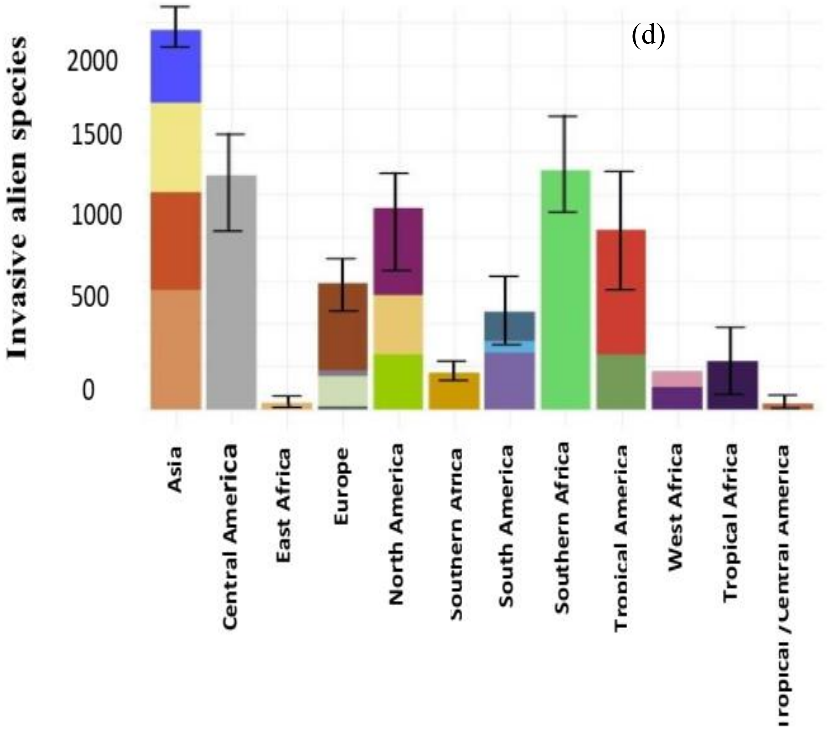


Figure 6: Invasive Alien Species

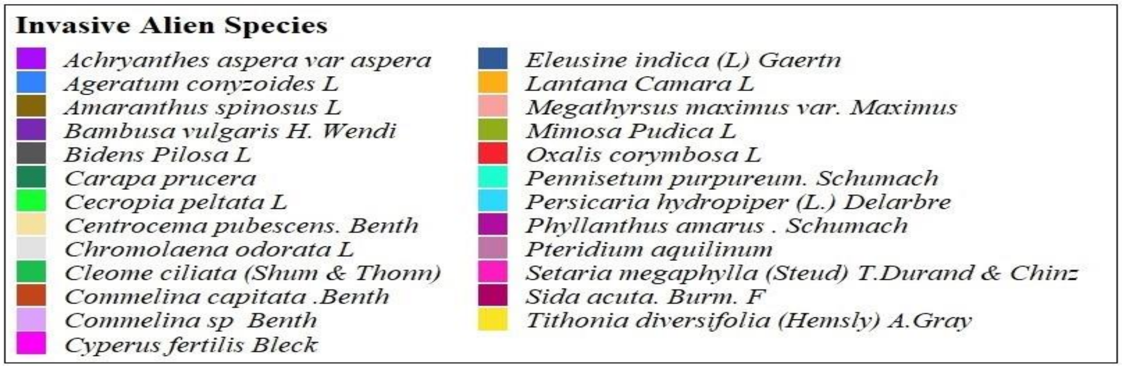


Figure 7: Relative Abundance (RA) of Invasive Alien Species Showing Their Similarities and Differences Across Sites in the Mount Cameroon Region

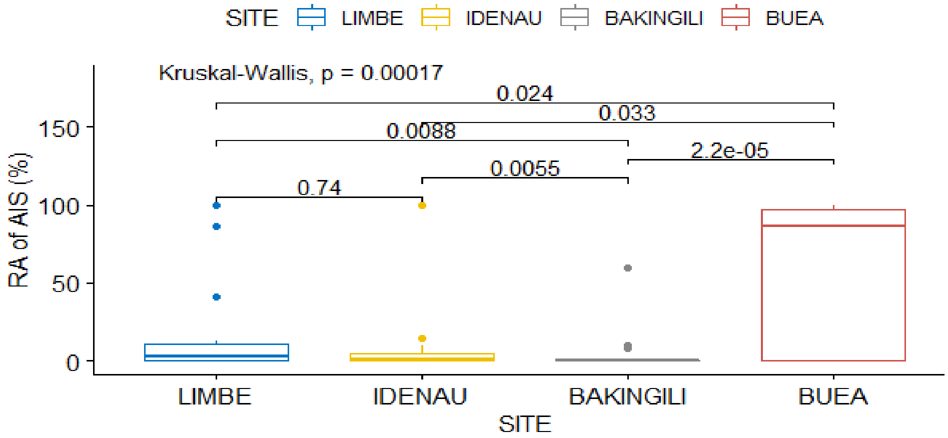
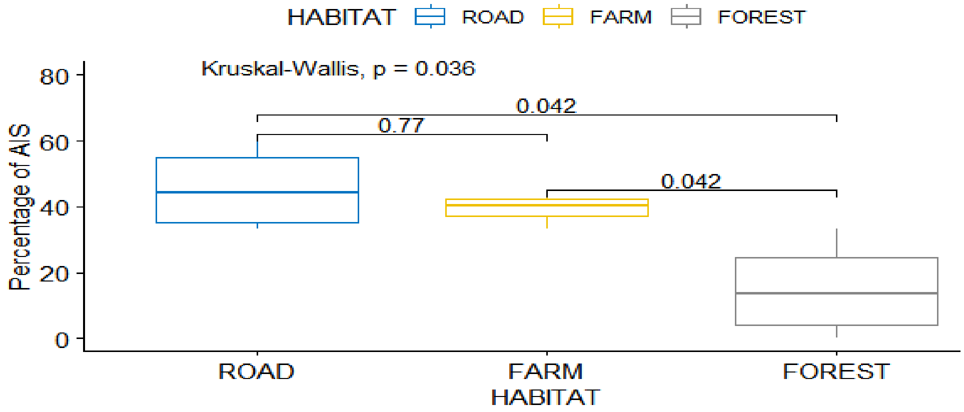


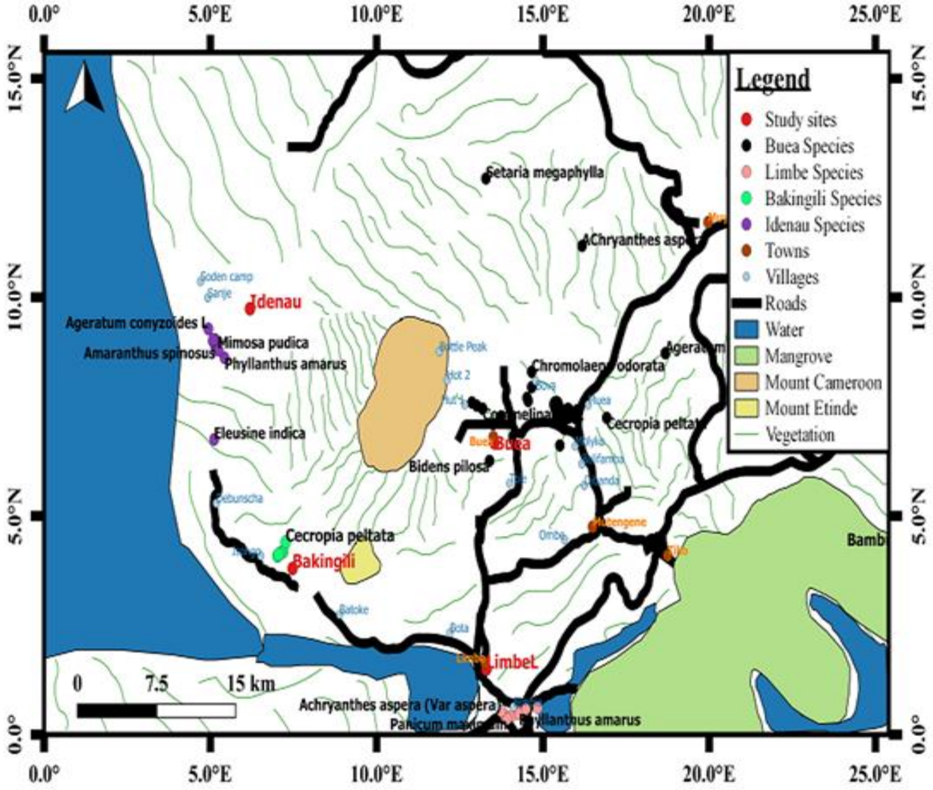
Figure 8: Occurrence of Invasive Alien Species by Habitat in the Study Sites in the Mount Cameroon Region



General Patterns of Distribution of Invasive Alien Species

Analysis of the distributional patterns of invasive alien species (IAS) across the four study sites in the Mount Cameroon region revealed marked spatial heterogeneity in both species richness and abundance (Figure 9). Buea emerged as the most heavily invaded site, harbouring 17 IAS, while Bakingili exhibited the lowest invasion intensity, with only three species recorded. In Bakingili, the IAS community was dominated by *Bambusa* *vulgaris*, which accounted for 28% of the total area invaded, reflecting the species' well-documented capacity for rapid vegetative and sexual propagation. Other notable species included *Tithonia diversifolia* (25.8%), *Chromolaena odorata* (20%), and *Cecropia peltata* (3%). The majority of invasions in Bakingili were concentrated along footpaths and agricultural lands, with *Bambusa vulgaris* being the most abundant and *Cecropia peltata* the least. Idenau recorded 16 IAS distributed across farms, forests, and roads, with roadsides supporting the highest species richness and forests the lowest. *Ageratum conyzoides* was the most prevalent species, covering 48% of the sampled area, whereas *Amaranthus spinosus* was the least common (2%). The IAS community in Idenau was composed exclusively of herbs and shrubs, exhibiting a bell-shaped distribution curve across habitats. In Limbe, 14 IAS were identified across all four surveyed land uses, spanning an elevation range of 0–197 m a.s.l. The cover crop *Centrosema pubescens* was the most widely distributed species (10.1% frequency). The only tree species observed was *Carapa procera*; all other IAS were herbs or shrubs. The overall distribution of IAS in Limbe displayed a U-shaped pattern, with higher frequencies at the extremes of the surveyed habitats. Buea, the most species-rich site, exhibited the broadest elevational and habitat range of IAS, from the low-lying University of Buea campus-where *Persicaria hydropiper* dominated flooded plains (30.7% coverage)-to the upper slopes of Mount Cameroon at approximately 3,000 m a.s.l., where *Eleusine indica* was prevalent. IAS were most frequently encountered along roadsides, followed by farmlands. Notably, 56% of the IAS in Buea were restricted to the mountain race tracks, highlighting the role of disturbance and elevation in structuring invasion patterns. Collectively, these findings underscore the pronounced variability in IAS distribution across the Mount Cameroon region, driven by site-specific factors such as land use, elevation, and disturbance regimes.

Figure 9: General Pattern of Distribution of Invasive Alien Species in the Mount Cameroon Region



Bayesian Modelling of Environmental and Species-Level Drivers of Invasive Alien Species Coverage in the Mount Cameroon Region (2020–2030)

Bayesian hierarchical modeling was employed to estimate and project the spatial dynamics of invasive alien species (IAS) coverage in the Mount Cameroon region from 2020 to 2030. The model intercept yielded a mean coefficient of 0.1272 (95% Credible Interval [CrI]: 0.0453, 0.1902), indicating a statistically significant positive baseline effect and suggesting that, under reference conditions, the IAS-occupied area is expected to increase by approximately 12.7% (Table 2). The percentage area occupied by individual IAS emerged as a strong predictor of overall proliferation, with a mean coefficient of 0.3636 (95% CrI: 0.2224, 0.4787). This finding implies that each 1% increase in the proportion of area occupied by IAS corresponds to a 36.4% rise in total IAS coverage, underscoring the critical role of local dominance in driving landscape-scale invasion.

Spatial autocorrelation was also significant: the spatial lag variable had a mean coefficient of 0.0244 (95% CrI: 0.0159, 0.0323), indicating that for every unit increase in geospatial proximity among IAS populations, the area covered increases by 2.4%. This highlights the influence of neighbouring infestations in facilitating local expansion.

Environmental interactions exerted notable effects on IAS dynamics. The interaction between temperature and humidity was positively associated with IAS expansion (mean coefficient: 0.1556; 95% CrI: 0.1423, 0.1719), suggesting that synergistic increases in these variables promote a 15.6% increase in IAS area. Conversely, interactions involving humidity with wind speed (mean: -0.2782; 95% CrI: -0.4620, -0.0349) and humidity with precipitation (mean: -0.6513; 95% CrI: -0.8127, -0.4899) were both negatively associated with IAS coverage, indicating that elevated humidity in combination with either wind or precipitation suppresses the spread of invasive species.

Other interactions, such as temperature with soil moisture and soil moisture with precipitation, exhibited negligible or statistically uncertain effects, as reflected by their wide credible intervals. Temporal and spatial heterogeneity in IAS dynamics was limited. In 2019, the interaction term for Buea indicated a modest but significant reduction in IAS area (mean coefficient: -0.0108; 95% CrI: -0.0182, -0.0033), corresponding to a 1.1% decrease. No significant temporal changes were observed in Limbe or in subsequent years (2020 and 2021), suggesting relative stability in invasion dynamics across these locations during the study period. Species-level analysis revealed substantial heterogeneity in the contribution of individual IAS to overall area expansion. *Carapa procera* exhibited the highest positive association (mean coefficient: 0.8200; 95% CrI: 0.4917, 1.1237), indicating that a 1% increase in its area is linked to an 82% increase in total IAS coverage. *Cecropia peltata* also showed a strong positive effect (mean: 0.6776; 95% CrI: 0.4040, 0.9242). Moderate positive associations were observed for *Commelina* sp. (0.2543), *Achyranthes aspera* (0.1078), *Bidens pilosa* (0.1059), and *Ageratum conyzoides* (0.0895). Several other species, including *Centrosema pubescens*, *Chromolaena odorata*, *Commelina capitata*, *Cyperus amarus*, *Cyperus fertilis*, *Eleusine indica*, *Lantana camara*, *Mimosa pudica*, and *Oxalis corymbosa*, also contributed positively, though to a lesser extent. In contrast, estimates for *Pennisetum purpureum*, *Phyllanthus amarus*, *Setaria megaphylla*, *Sida acuta*, and *Tithonia diversifolia* exhibited considerable uncertainty, as indicated by their wide credible intervals. Collectively, these results highlight the multifaceted drivers of IAS expansion in the Mount Cameroon region. Local dominance, spatial proximity, and specific environmental interactions are key determinants of invasion dynamics, while species-specific traits further modulate the extent of area occupied. These insights are critical for informing targeted management and forecasting future invasion risks under changing climatic and land-use scenarios.

Table 2: Coefficients of Factors Influencing Invasive Alien Species Coverage

Variable	Mean (log IAS area)	Lower CrI	Upper CrI
% area per IAS	0.3636	0.2224	0.4787
Spatial lag variable	0.0244	0.0159	0.0323
IAS unite area × Native species unit area	0.0060	-0.0037	0.0153
Temperature × Humidity	0.1556	0.1423	0.1719
Humidity × Wind Speed	-0.2782	-0.4620	-0.0349
Temperature × Soil Moisture	-0.0011	-0.0099	0.0072
Humidity × Precipitation	-0.6513	-0.7099	-0.6017
Soil Moisture × Precipitation	-0.0216	-0.0692	0.0287
Year × Location			
2019 × Buea	-0.0108	-0.0182	-0.0033
2019 × Limbe	-0.0042	-0.0099	0.0023
2020 × Buea	0.0006	-0.0049	0.0053
2020 × Limbe	-0.0013	-0.0139	0.0098
2021 × Buea	-0.0012	-0.0085	0.0074
2021 × Limbe	0.0074	-0.0015	0.0162
IAS × IAS count			
Achryanthes aspera	0.1078	0.0787	0.1339
Ageratum conyzoides	0.0895	0.0648	0.1124
Bidens pilosa	0.1059	0.0777	0.1330
Carapa prucera	0.8200	0.4917	1.1237
Cecropia peltata	0.6776	0.4040	0.9242
Centrocema pubescens	0.0224	0.0117	0.0353
Chromolaena odorata	0.0196	0.0095	0.0312
Commelina SP	0.2543	0.1486	0.3528
Commelina capitata	0.0389	0.0294	0.0484
Cyperus amarus	0.0509	0.0313	0.0718
Cyperus fertilis	0.0231	0.0115	0.0351
Eleusine indica	0.0141	0.0052	0.0250
Lantana camara	0.0146	0.0011	0.0274
Mimosa pudica	0.0239	0.0088	0.0397
Oxalis corymbosa	0.0250	0.0032	0.0468
Pennisetum purpureum	0.0024	-0.0200	0.0257
Phyllanthus amarus	0.0021	-0.0149	0.0197
Setaria megaphylla	-0.0028	-0.0292	0.0247
Sida acuta	-0.0087	-0.0257	0.0098
Tithonia diversifolia	-0.0106	-0.0251	0.0042
Sigma	0.7557	0.5081	1.1252
_cons	0.1272	0.0453	0.1902

CrI = (95%) Credible Interval; The standard deviation of the residuals (Sigma) [0.7557 (95% CrI: 0.5081, 1.1252) indicates moderate variability in the model's predictions.

Projected Species-Specific Trends in Invasive Alien Species Area (2020–2030)

Bayesian modeling of projected area trends for invasive alien species (IAS) in the Mount Cameroon region indicates a consistent expansion of all recorded species from 2022 through 2030. The projections incorporated key ecological drivers, such as site-specific rainfall patterns, ensuring robust scenario-based forecasting. Model outputs revealed that the area occupied by each IAS is expected to increase steadily over the decade, with the peak of each species' expansion curve denoting the period of maximal spatial proliferation (Fig. 10). Notably, *Eleucine indica*, *Chromolaena odorata, Centrocema pubescens*, and *Tithonia diversifolia* are projected to experience the most substantial increases, each potentially reaching an occupied area of approximately 140 m² by 2030. In contrast, *Carapa procera* is predicted to exhibit the lowest expansion among the assessed species. The dominance of *Tithonia diversifolia* and *Chromolaena odorata* in projected trends is attributable to their aggressive colonisation strategies, high reproductive rates, and adaptability to disturbed habitats, such as roadsides, abandoned farmlands, and hedgerows. These characteristics are likely to sustain their status as the most pervasive invasive weeds in the Mount Cameroon region, with their influence potentially persisting through 2050 if current trends continue.

Collectively, these projections underscore the urgent need for targeted management interventions focused on the most rapidly expanding IAS, particularly *Eleucine indica* and *Chromolaena odorata*, to mitigate further ecological and economic impacts in the region.

Projected Annual Change in Invasive Alien Species Area from 2020-2030 in the Mount Cameroon Region

Figure 11 presents the projected annual spatial expansion of invasive alien species (IAS) in the Mount Cameroon region from 2020 to 2030. The analysis reveals that *Eleusine indica* and *Chromolaena odorata* are anticipated to be the most dominant IAS throughout the projection period, as evidenced by their consistently broad bands of spread. In contrast, *Commelina* sp. is projected to have the least spatial expansion among the species analysed.

By 2030, the cumulative area occupied by IAS in the region is expected to surpass 75,000 m², underscoring the accelerating pace of biological invasion. Notably, *Chromolaena odorata* demonstrates particularly aggressive expansion dynamics, being recorded across a wide range of habitats and consistently ranking among the most prevalent invasive species in the region.

These projections highlight the urgent need for proactive management strategies targeting the most rapidly expanding and ecologically disruptive IAS, particularly *Chromolaena odorata* and *Eleusine indica*, to mitigate their long-term impacts on native biodiversity and ecosystem function.

Figure 10: Projected Invasive Alien Species Area Trend by Species from 2020-2030 in the Mount Cameroon Region

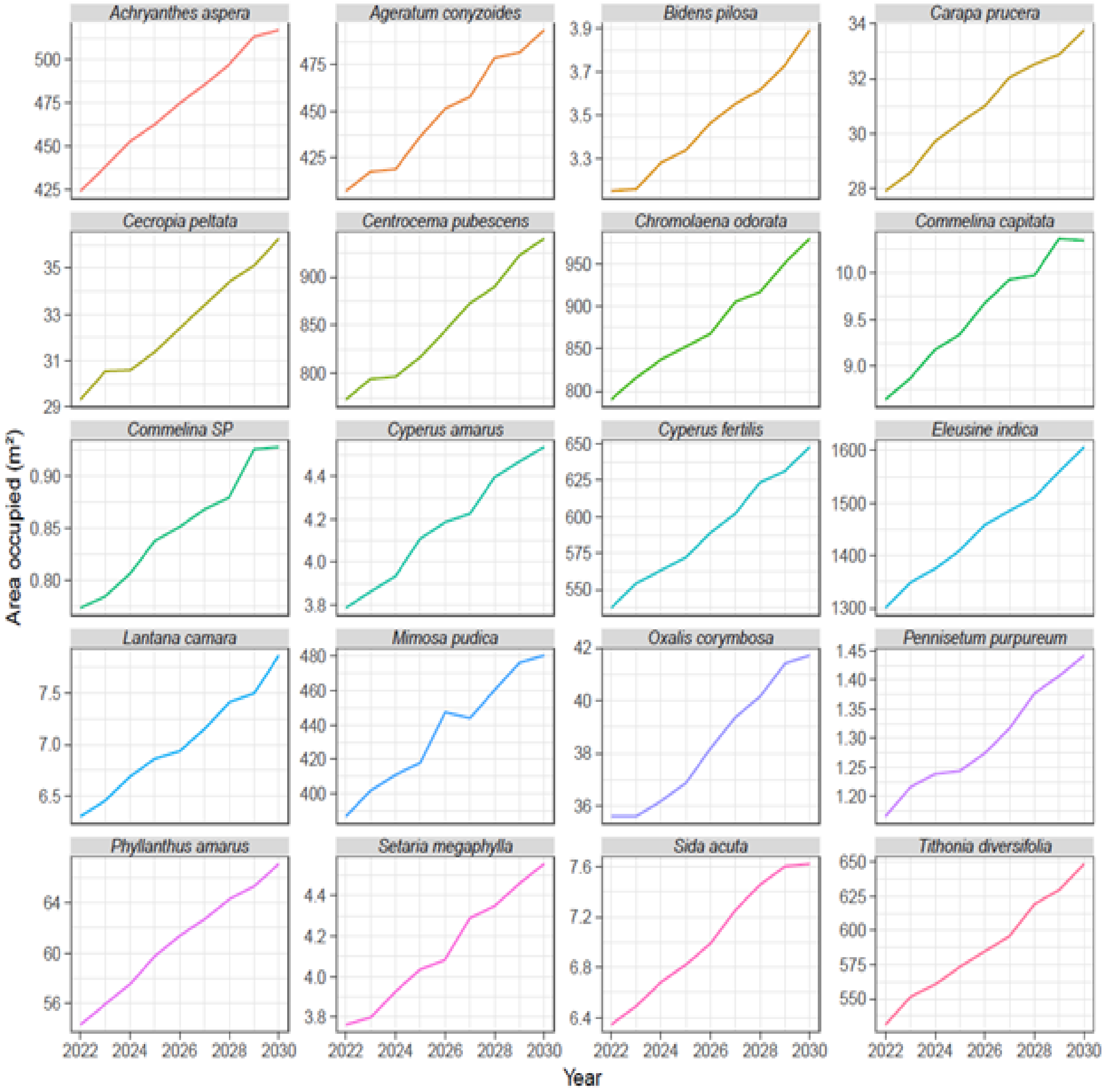
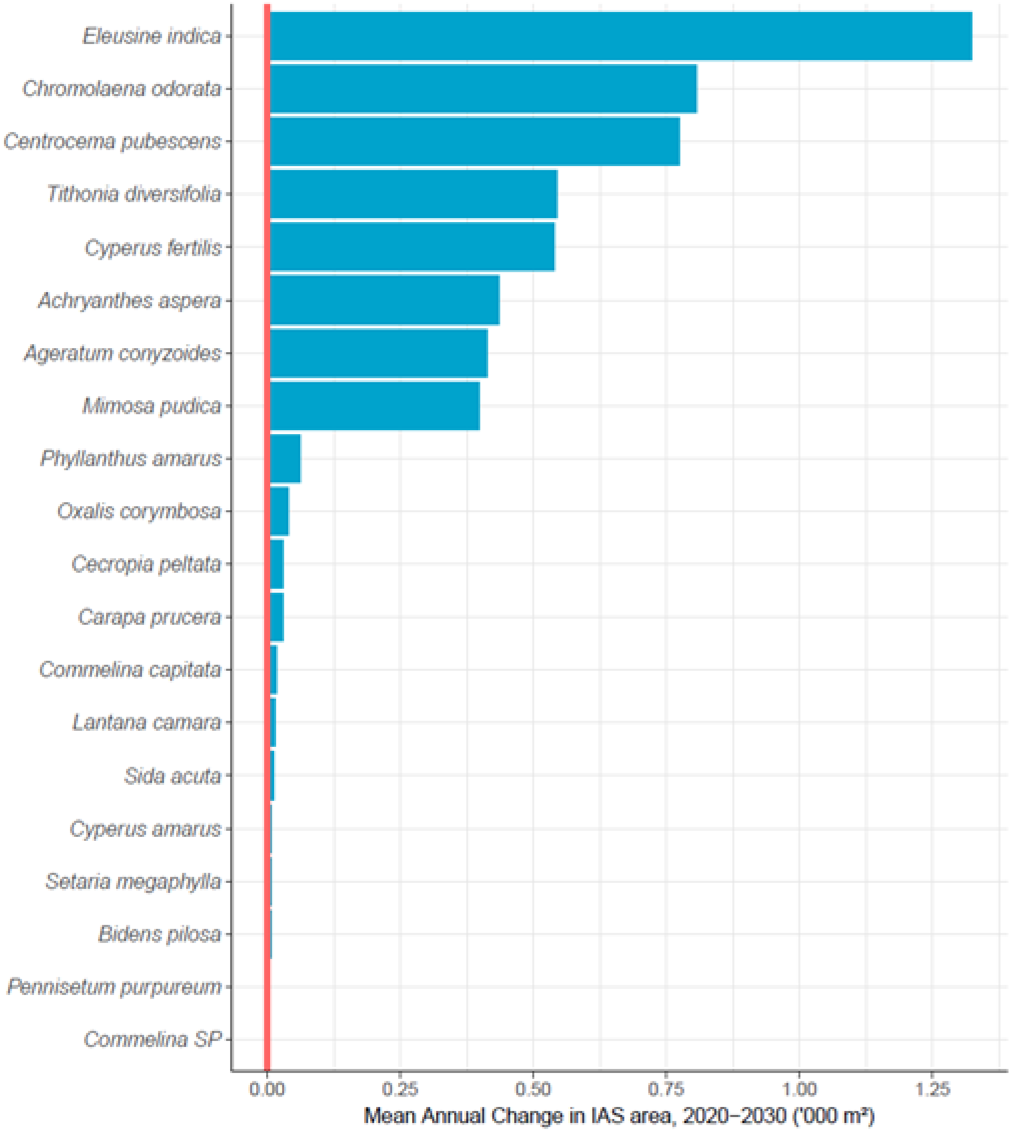


Figure 11: Projected Annual Change in Invasive Alien Species Area from 2020-2030 in the Mount Cameroon Region



Diversity Indices of Invasive Alien Species Across Sites in the Mount Cameroon Region

A comparative analysis of diversity indices—Shannon-Wiener diversity (H′), species richness (S), and evenness (E)—across invaded and uninvaded vegetation in the Mount Cameroon region reveals marked spatial heterogeneity in the structure of invasive alien species (IAS) communities (Table 3). Among the study sites, Buea consistently exhibited the highest diversity and richness of IAS, particularly in uninvaded habitats (H′ = 2.59; S = 17.30), indicating a rich and more evenly distributed assemblage of species. In contrast, Bakingili recorded the lowest diversity (H′ = 1.21) and richness (S = 4.00) in invaded sites, reflecting a more depauperate and potentially more dominated community structure. Evenness values further elucidate these patterns. The highest evenness (E = 0.96) was observed in uninvaded vegetation in Buea, suggesting a relatively uniform distribution of individuals among species. Conversely, the lowest evenness was recorded in invaded habitats of Limbe (E = 0.56), and similarly low values were observed in Idenau, indicating that a few species dominate these communities, a common pattern in heavily invaded ecosystems. These findings reflect the profound impact of biological invasion on community structure, with invaded habitats generally supporting lower diversity, richness, and evenness compared to their uninvaded counterparts. The pronounced differences among sites highlight the influence of local environmental factors and invasion histories on the composition and structure of IAS communities across the Mount Cameroon landscape.

Table 3: Shannon Wiener's Diversity Indices (H'), Species Richness(S) and Evenness (E) of Invasive Alien Species Across Sites in the Mount Cameroon Region

Parameter	Invaded				Uninvaded			
	Limbe	Bakingili	Buea	Idenau	Limbe	Bakingili	Buea	Idenau
H'	1.38	1.21	2.57	2.22	1.41	1.23	2.59	2.30
E	0.56	O.87	0.91	0.80	0.62	0.92	0.96	0.81
S	12.00	4.00	17.00	16.00	12.70	4.60	17.30	16.20

DISCUSSION

Taxonomic and Functional Diversity of Invasive Alien Species

This study presents the first systematic inventory and ecological assessment of invasive alien plant species (IAS) in the Mount Cameroon region, revealing a strikingly diverse assemblage of 25 IAS spanning 16 families and 24 genera. The predominance of Asteraceae and Poaceae aligns with global invasion patterns, as these families are renowned for their ecological plasticity, prolific seed production, and efficient dispersal mechanisms (Sengupta & Dash, 2020; Rusdy, 2020; Rai et al., 2022). The observed heterogeneity in family composition across sites—such as the unique presence of Oxalidaceae and Polygonaceae in Buea, and Cleomaceae and Pteridaceae in Idenau—reflects both historical introduction pathways and local environmental filters. Growth form analysis indicated a clear dominance of annual herbs, which constituted 70% of the IAS pool. This pattern is consistent with the literature, as herbaceous invaders often exhibit rapid life cycles, high reproductive rates, and a capacity to exploit disturbed environments (Pyšek & Hulme, 2005; Inderjit et al., 2018). The prevalence of herbs may also be attributed to their frequent use in floriculture and their ability to propagate via both seeds and vegetative means, enhancing their invasive potential (Mehraj et al., 2018).

Spatial Patterns and Habitat Associations

IAS were detected across all surveyed land uses—roadsides, farmlands, and forests—but their frequency was markedly highest along roadsides, especially in Limbe, Idenau, and Buea. This pattern underpins the role of anthropogenic disturbance, habitat fragmentation, and transport corridors in facilitating biological invasions (Benedetti & Morelli, 2017; Oh et al., 2021). Roads act as vectors for propagule dispersal and create microhabitats conducive to establishment, a phenomenon widely documented in invasion ecology (Höfle et al., 2014; Bhatta et al., 2020). The relatively low invasion intensity in Bakingili may be attributed to its larger protected area and reduced human disturbance, providing refugia for native flora.

Biogeographic analysis revealed that most IAS originated from Asia, Europe, and North America, reflecting the influence of global trade, tourism, and migration on propagule pressure and introduction pathways (Hulme, 2009; Sirbu et al., 2022). The correspondence between species' origins and the predominant regions of international visitors to Mount Cameroon further highlights the role of human-mediated dispersal.

Abundance, Distribution, and Community Impact

Quantitative analyses demonstrated significant spatial variation in IAS abundance, with Buea exhibiting the highest levels and Bakingili the lowest. The dominance of species such as *Centrosema pubescens* in Limbe and *Bambusa vulgaris* in Bakingili illustrates the importance of species-specific traits—such as rapid vegetative spread and tolerance to a range of environmental conditions—in shaping local invasion dynamics (Anning & Yeboah-Gyan, 2007; GISD, 2013). The pronounced reduction in diversity, richness, and evenness in invaded plots compared to uninvaded ones, particularly in Buea and Limbe, highlights the profound impact of IAS on native community structure. Invaders such as *Tithonia diversifolia* and *Chromolaena odorata* form dense monocultures, outcompeting native species for resources and altering ecosystem function (Hejda et al., 2009; Pyšek et al., 2017). This is consistent with findings from other tropical regions, where aggressive IAS reduce native species diversity and homogenise plant communities (Hulme & Bremner, 2006; Hejda & Pyšek, 2006).

Environmental and Species-Level Drivers of IAS Expansion

Bayesian hierarchical modelling identified several key drivers of IAS expansion. The percentage area occupied by individual IAS was a strong predictor of overall proliferation, underscoring the role of local dominance in facilitating landscape-scale invasion. Spatial autocorrelation further highlighted the influence of neighbouring infestations, with proximity accelerating spread.

Environmental interactions exerted complex effects: while synergistic increases in temperature and humidity promoted IAS expansion, elevated humidity combined with wind or precipitation suppressed spread. These findings suggest that climate variability and microclimatic conditions may modulate invasion trajectories, with implications for management under future climate scenarios (Pabst et al., 2022). At the species level, *Carapa procera* and *Cecropia peltata* exhibited the strongest positive associations with area expansion, while several other species, including *Tithonia diversifolia* and *Chromolaena odorata*, were projected to remain dominant invaders due to their high reproductive capacity, allelopathic effects, and adaptability to disturbed habitats (Obiakara & Fourcade, 2018; Witt et al., 2019).

Projections and Management Implications

Model projections indicate a persistent and accelerating expansion of IAS in the Mount Cameroon region through 2030, with the cumulative occupied area expected to exceed 75,000 m² by 2030. The most aggressive species, notably *Chromolaena odorata* and *Eleusine indica*, are anticipated to dominate the landscape, particularly along roadsides and disturbed sites. These trends mirror global patterns of IAS spread in response to increasing anthropogenic disturbance and climate change (Vicente et al., 2019; Seebens et al., 2021). The results unravel the urgent need for targeted, site-specific management interventions. Priority should be given to high-risk areas such as roadsides and urban centres, and the most rapidly expanding species. Early detection, rapid response, and sustained control efforts, coupled with public awareness and biosecurity measures, are essential to mitigate the ecological and economic impacts of IAS in the region (Hulme, 2009; Pyšek et al., 2017; van Kleunen et al., 2018).

Taxonomic and Functional Diversity of Invasive Alien Species

This study provides the first comprehensive ecological inventory of invasive alien plant species (IAS) along the Mount Cameroon gradient, documenting 25 IAS across 16 families and 24 genera. The dominance of Asteraceae and Poaceae aligns with global invasion trends, reflecting these families' high ecological plasticity, reproductive output, and effective dispersal strategies (Sengupta & Dash, 2020; Rusdy, 2020; Rai et al., 2022). A high prevalence of annual herbs (70% of identified IAS) reinforces observations across tropical systems, where fast-growing, propagule-rich herbs rapidly exploit disturbed environments (Pyšek & Hulme, 2005; Inderjit et al., 2018; Mehraj et al., 2018).

Notably, species composition showed spatial variability—some families (eg, Oxalidaceae in Buea, Pteridaceae in Idenau) were unique to particular sites—demonstrating how introduction history and local environmental filters shape invasion identity. This spatial heterogeneity has implications for management planning, as site-specific taxa may require targeted interventions rather than generalised region-wide strategies.

Spatial Patterns and Invasion Hotspots

IAS were present in all target habitats but were most frequent and abundant along roadsides, highlighting the role of anthropogenic disturbances and edge effects in facilitating establishment and spread (Benedetti & Morelli, 2017; Oh et al., 2021). Roads in Limbe, Idenau, and Buea emerged as key invasion corridors—reflecting their function as dispersal conduits and disturbed microhabitats (Höfle et al., 2014; Bhatta et al., 2020). Conversely, Bakingili exhibited notably lower invasion levels, likely due to lower human activity and the presence of conservation zones that limit disturbance and introduction pressure.

Biogeographic origin analysis traced most IAS to Asia, Europe, and North America, consistent with pathways tied to trade, tourism, and migration (Hulme, 2009; Sirbu et al., 2022). This finding affirms the link between global connectivity and propagule pressure—particularly relevant for Mount Cameroon given its designation as a national park and tourist hub.

Ecological Effects and Dominance Patterns

Significant variation in IAS abundance across sites was observed, with species-specific dominance reflecting varying adaptation strategies. *Centrosema pubescens* and *Bambusa vulgaris*, for example, achieved local dominance through vegetative spread and environmental tolerance (Anning & Yeboah-Gyan, 2007; GISD, 2013). Such traits support rapid occupancy and landscape transformation. Across sites, IAS presence correlated strongly with reduced native species richness, evenness, and diversity, particularly in Limbe and Buea. Aggressive species such as *Tithonia diversifolia* and *Chromolaena odorata* are capable of forming dense monospecific stands that displace native flora and modify ecosystem structure—effects well-documented in tropical systems (Hejda et al., 2009; Hulme & Bremner, 2006; Hejda & Pyšek, 2006; Pyšek et al., 2017).

Environmental and Species-Specific Drivers

Bayesian modeling identified species area coverage and spatial autocorrelation as key predictors of IAS expansion—underscoring how local dominance and proximity to existing infestations accelerate spread. Environmental interactions were nuanced: warmer temperatures and higher humidity generally promoted expansion, while increased precipitation and strong winds under high humidity appeared to constrain spread. These context-dependent interactions suggest that microclimatic variability can shift invasion trajectories, a finding with relevance to climate change adaptation (Pabst et al., 2022). At the species level, *Carapa procera* and *Cecropia peltata* demonstrated strong positive association with landscape-level expansion, while other high-impact taxa like *Tithonia diversifolia* and *Chromolaena odorata* are predicted to maintain dominance due to their competitive traits and ecological generalism (Obiakara & Fourcade, 2018; Witt et al., 2019).

Projected Spread and Management Priorities

Model outputs project that the area under IAS will exceed 75,000 m² in the Mount Cameroon region by 2030, reflecting accelerating expansion trends. Disturbed habitats and roadsides are expected to remain the most affected zones, with species like *Chromolaena odorata* and *Eleusine indica* projected to become increasingly dominant—patterns consistent with broad global invasion trajectories (Vicente et al., 2019; Seebens et al., 2021). This underscores the urgent need for proactive, site-specific control strategies. Early detection and rapid response should be prioritised in known invasion hotspots. Ecological monitoring, public awareness, and biosecurity at entry points must accompany mechanical or biological controls to prevent irreversible ecosystem shifts (Hulme, 2009; Pyšek et al., 2017; van Kleunen et al., 2018).

CONCLUSION

This study provides the first comprehensive assessment of invasive alien plant species (IAS) in the Mount Cameroon region, documenting 25 species across 16 families and 24 genera. Asteraceae and Poaceae emerged as the most dominant families, with annual herbs predominating the invasive flora. Spatial analysis revealed significant heterogeneity in IAS distribution, with roadsides and farmlands acting as primary invasion hotspots due to anthropogenic disturbances and high propagule pressure. Most IAS originated from Asia, Europe, and North America, highlighting the role of global trade and human activity in species introduction.

Quantitative results showed that IAS significantly reduce native plant diversity, richness, and evenness—effects most pronounced in disturbed areas like Buea and Limbe. Bayesian hierarchical modeling identified both environmental conditions (eg, temperature, humidity, proximity to established populations) and species traits (eg, growth type, reproductive capacity) as major drivers of spread. Projections suggest a continued and accelerated expansion of dominant species such as *Chromolaena odorata*, *Tithonia diversifolia*, and *Eleusine indica*, potentially exceeding a cumulative spread of 75,000 m² by 2030.

These findings underscore the urgent need for proactive and spatially targeted management strategies. The integration of GIS and hierarchical modeling offers a robust framework for identifying priority control areas and anticipating future invasion risks under shifting environmental conditions.

To effectively manage invasive alien species (IAS), it is essential to prioritise early detection, implement species-specific control measures, and establish consistent monitoring systems. Public awareness campaigns and strengthened biosecurity measures should be promoted to prevent new introductions and enhance community engagement. Additionally, restoring native vegetation is critical for improving ecosystem resilience in invaded areas. Long-term ecological research is essential for developing context-specific strategies that support biodiversity and ecosystem function. Future studies should focus on post-invasion ecosystem responses, including impacts on nutrient cycling and forest regeneration, while also accounting for the influence of climatic variability on invasion dynamics.

Acknowledgements: We thank the people of the Mount Cameroon Region for allowing the research team to explore their communities to document the invasive alien species.

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