ASIAN JOURNAL OF FORESTRY
Volume 8, Number 2, December 2024 E-ISSN: 2580-2844
Pages: 184-193 DOI: 10.13057/asianjfor/r080209

Species distribution modelling to identify invasion hotspots of *Ageratina riparia* in Mizoram, India

RABISHANKAR SENGUPTA[1,♥], SUDHANSU S. DASH[2]
[1]Central National Herbarium, Botanical Survey of India. Howrah 711103, India. Tel. +91-9073012031, ♥email: sengupta.rabishankar@gmail.com
[2]Botanical Survey of India. CGO Complex, DF Block, Sector 1, Kolkata 700019, India

Manuscript received: 31 August 2024. Revision accepted: 13 December 2024.

Abstract. *Sengupta R, Dash SS. 2024. Species distribution modelling to identify invasion hotspots of* Ageratina riparia *in Mizoram, India. Asian J For 8: 184-193.* The accelerated pace of globalization, increased human mobility, and the intensification of global trade have significantly amplified the spread of non-native species worldwide. The introduction of these alien species has triggered invasive consequences, further intensified by climate change. Accurately predicting the spread of invasive species under changing climatic conditions is essential for identifying vulnerable regions and formulating effective management strategies to limit their spread. This study projected and identified invasion hotspots for the neo-invasive species *Ageratina riparia* in Mizoram, using its current distribution patterns and projected climate changes. Habitat suitability modelling, performed with the Maximum Entropy (MaxEnt) machine learning algorithm using default settings, showed that the current distribution of *A. riparia* encompasses 4.78% of Mizoram's area, deemed suitable for varying levels of invasion. Projections for 2050 and 2070 indicated that suitable habitats for *A. riparia* could expand to 6.19% of Mizoram's area by 2050 under the RCP 4.5 scenario, relative to its present distribution. This anticipated expansion, combined with an upward shift in elevation, highlights the urgent need for effective management strategies to mitigate the invasion by *A. riparia*. The findings provide critical insights for identifying and projecting invasion hotspots, which are essential for early-stage management of *A. riparia* invasions.

Keywords: *Ageratina riparia*, alien plants, Asteraceae, habitat suitability, MaxEnt, plant invasion

Abbreviations: AUC: Area Under the Curve, IAPs: Invasive alien plants, TSS: True Skill Statistic

INTRODUCTION

In recent years, invasive alien plants (hereafter IAPs) have emerged as significant drivers of global environmental change, posing immediate threats to biodiversity, ecosystem services, and ecosystem functions (Vilà et al. 2010; Adhikari et al. 2023). Richardson and Rejmánek (2011) projected that the ongoing progression of global climate change would gradually intensify the incidence of invasions within natural forests. The combined effects of human activities and global climate change are critical factors contributing to the widespread establishment and expansion of IAPs.

Understanding the complex interactions between climate change and IAPs, however, remains challenging (Merow et al. 2017). Key challenges in the study of biological invasions include identifying invasive traits of alien species, assessing habitat vulnerabilities, evaluating the impacts of invasions, predicting invasive tendencies, and developing effective management strategies for invasions within natural forest ecosystems (Essl et al. 2020). The first three of these challenges represent core research areas within biological invasion studies, and a thorough understanding of these aspects provides a solid foundation for effective control and management of biological invasions (Mačić et al. 2018). Consequently, the primary objective of biological invasion research is to control and manage alien plant invasions in specific natural forested regions (Ahmed et al. 2022).

Ageratina riparia (Regel) R.M. King & H. Rob., introduced to India as an ornamental plant in the early 1900s, likely spread to Mizoram during the Second World War through contaminated meadow and forest seeds (Sengupta and Dash 2020). In invasion scenarios, this IAP poses serious risks to natural forests, protected areas, and agricultural lands in Mizoram (Sengupta and Dash 2023b).

A. riparia is a perennial herb or sub-shrub with an erect growth form, characterized by a slender, striated stem reaching heights of 30 cm to 1 m. The plant has simple, oppositely arranged leaves with tapered petioles, featuring narrowly lanceolate to elliptical blades that taper at both ends and display irregular serrations. The leaf surfaces are smooth on top, with short hairs beneath. Small, bell-shaped clusters of capitula form loose inflorescences, with each capitulum containing approximately 20-25 tubular white florets (Figure 1). The fruit is a black achene with five ribs and a pappus tuft. The rounded, striated stem can reach up to 1-1.5 m in height (Sengupta and Dash 2020).

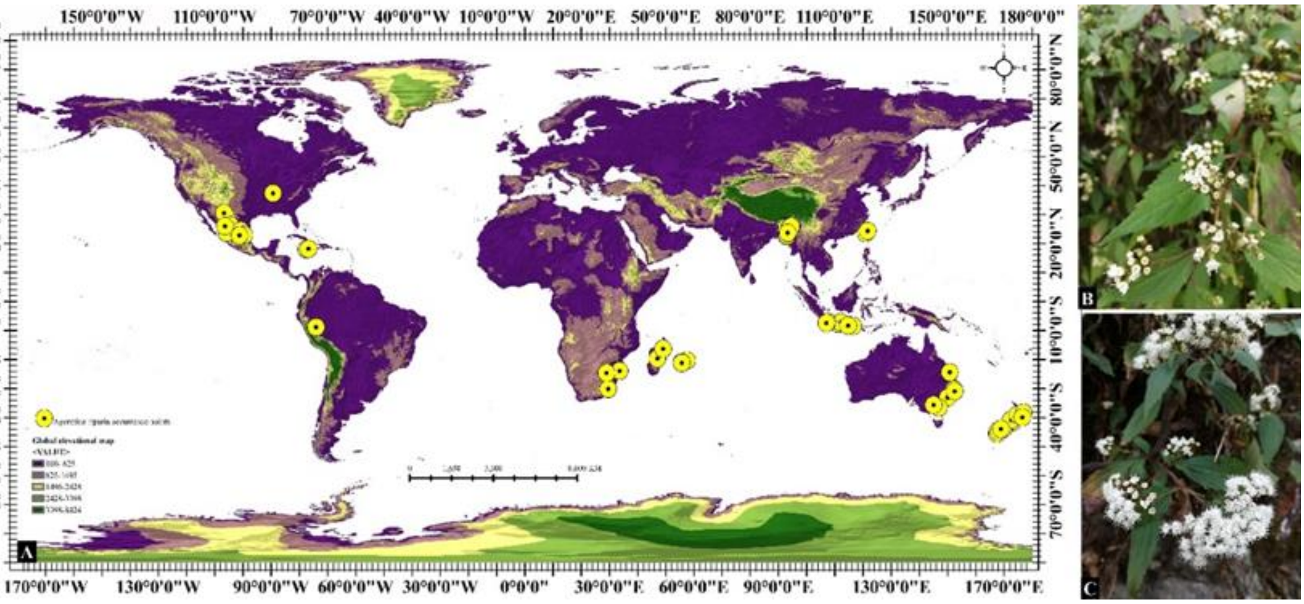

Figure 1. A. Global distribution of *Ageratina riparia* (yellow points) occurrence, B. Habit, C.Flower close up

The distribution of many invasive species is increasingly shaped by human-facilitated movement, which threatens biodiversity, agriculture, disrupts ecosystems, and hampers conservation efforts (Adhikari et al. 2015). Anthropogenic environmental changes, such as nitrification, elevated CO_2 levels, and shifting climate patterns, can promote invasive plant species by increasing the availability of limiting resources (Hautier et al. 2015). In light of these human-driven environmental shifts, species distribution modelling can be employed at early stages to predict climate change impacts and identify potential invasion hotspots.

A critical initial management step to mitigate the impact of alien plants on native vegetation is to assess their invasiveness potential, especially in the context of climate change (Fournier et al. 2019). Ecological Niche Modelling (ENM), or Species Distribution Modelling (SDM), uses mathematical algorithms, species occurrence data, and environmental variables to predict species distribution (Valavi et al. 2022). SDM has proven to be a valuable tool for examining the impact of Invasive Alien Plants (IAPs) and predicting future spread. For instance, the Maximum Entropy (MaxEnt) algorithm has been applied to predict the distribution of *Ageratina adenophora* (Spreng.) R.M.King & H.Rob. in South Africa (Tererai and Wood 2014) and Nepal (Poudel et al. 2020), *Mikania micrantha* Kunth in India (Rameshprabu and Swamy 2015), *Chromolaena odorata* (L.) R.M.King & H.Rob. in the Eastern Ghats (Saranya et al. 2021) and Mizoram (Sengupta and Dash 2023b). Recent studies have assessed potential shifts in IAP distributions under various climate change scenarios at regional (Adhikari et al. 2015) and global scales (Vaz et al. 2018). Using SDMs and bioclimatic data, these studies have identified invasion hotspots for alien plants across North-East India, such as *Ageratum conyzoides* L. and *Imperata cylindrica* (L.) Raeusch. (Ray et al. 2019), Assam for *M. micrantha* (Choudhury et al. 2021), Jammu & Kashmir for *Parthenium hysterophorus* L. (Mushtaq et al. 2021), Eastern India for *Lantana camara* L. (Tiwari et al. 2022), South East Asia for *Tithonia diversifolia* (Hemsl.) A. Gray (Boral and Moktan 2022), and Mizoram for *C. odorata* (Sengupta and Dash 2023b). However, studies on the potential invasion of neo-invasive species such as *A. riparia* in the Indian Himalayan Region (IHR), including Mizoram, remain limited. MaxEnt modelling relies on species occurrence data and environmental variables to estimate potential habitats for invasive species, demonstrating high predictive accuracy (Phillips and Dudík 2008; Phillips et al. 2017).

Managing and preventing the invasion of *A. riparia* is both costly and time-consuming. However, predictive modelling can help identify future invasion hotspots, which is crucial for anticipating the spread of *A. riparia* in Mizoram. Currently, no studies have addressed the prediction of future invasion scenarios for this species in Mizoram. To fill this gap, our study evaluates the potential invasion and establishment of *A. riparia* in Mizoram's natural forests using the MaxEnt model for habitat suitability. We utilized current occurrence data for *A. riparia*, along with environmental and anthropogenic factors affecting its spread. This research aims to provide decision-makers with essential insights to develop effective strategies for the prevention and management of *A. riparia* invasion in Mizoram.

MATERIALS AND METHODS

Study sites

The study was conducted in Mizoram, located within the Indo-Burma biodiversity hotspot (Figure 1). Field research was carried out between July 2021 and September 2023, focusing on floristic and ecological surveys across various regions of Mizoram, including protected areas, as part of the lead author's doctoral research. Mizoram is bordered by the Indian states of Tripura, Assam, and Manipur to the west, north, and east, respectively. Forests cover 84.53% of Mizoram's total geographical area, with only 6.75% designated as protected areas. The region experiences summer temperatures ranging from 18°C to 29°C (March to May) and winter temperatures ranging from 11°C to 24°C (August to December), with an annual rainfall between 2,160 mm and 3,500 mm (FSI 2021).

Species occurrence data

Occurrence data for *A. riparia* was collected through field surveys during the floristic and ecological assessments. Geographic coordinates were recorded with a Garmin Montana 680 GPS device, resulting in 228 unique occurrence points for this neo-invasive species in Mizoram. These coordinates were incorporated into a digital elevation map of the study area (Figure 2). The data underwent screening to remove any erroneous or duplicate records outside the study area, maintaining a 1 km (30 arc-seconds) minimum distance between points using ArcGIS (ArcMap 10.8.2) to ensure data quality. To enhance model accuracy and reduce sampling bias, a presence-background approach with site-occupancy data was employed (Botella et al. 2020).

Bioclimatic and environmental variables

Elevation and environmental data (Table 1) for both current and future climate scenarios were sourced from the WorldClim global database (Hijmans et al. 2005) at a resolution of ~1 km² (30 arc-seconds). Future climate projections were based on 19 bioclimatic variables under RCP 2.6, 4.5, and 8.5 scenarios for the years 2050 and 2070, utilizing the GFDL-CM3 climate model (CMIP5; Griffies et al. 2011). The Mizoram study area was extracted, and data was converted to ASCII format in ArcGIS 10.8.2. To ensure model robustness, only uncorrelated variables were selected for MaxEnt modelling, with multicollinearity ($r > 0.9$) eliminated using SDM Toolbox 2.0 (Brown et al. 2017). Models were developed with a 30% random test set, and ten replicated runs were executed to produce average, maximum, minimum, median, and standard deviation outputs for each run (Thapa et al. 2018).

Table 1. Uncorrelated bioclimatic variables used in the study (source: https://www.worldclim.org/)

Abbreviation	Bioclimatic variables
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (×100)
BIO5	Max Temperature of Warmest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO12	Annual Precipitation
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter
Elev	Elevation

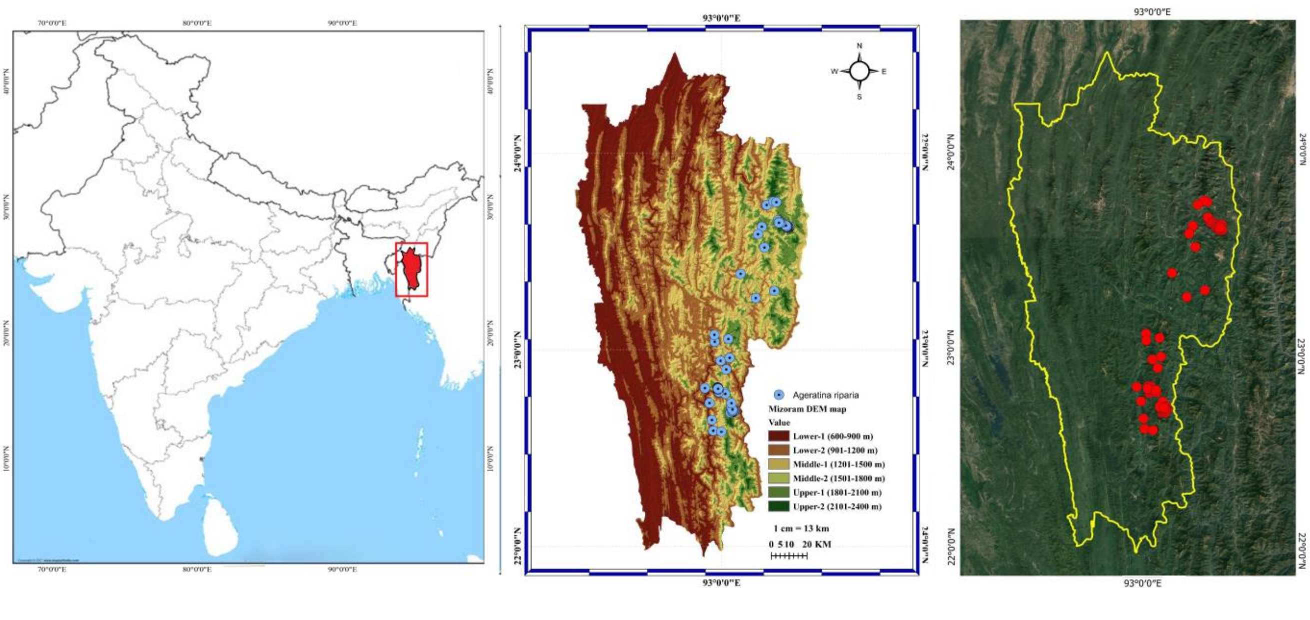

Figure 2. The digital elevation map of Mizoram, India showing the present occurrence points of *Ageratina riparia*

Model building and evaluation

The MaxEnt algorithm (version 3.4.4), a 'presence-only' machine learning approach (Phillips et al. 2023), was employed to identify suitable habitats for *A. riparia* under current and future climate scenarios. This approach allows modelling of the species' fundamental niche based on environmental variables. Only uncorrelated bioclimatic variables (Tables 1 and 2) were incorporated, following a 10-percentile training presence threshold rule with ten replications and auto feature settings enabled. MaxEnt delineates ecological niche boundaries by constraining the probability distribution to the environmental parameters associated with species presence at grid-cell locations (Phillips et al. 2017). Models were run using default settings with uncorrelated variables. To evaluate model accuracy, Area Under the Curve (AUC) values were interpreted as follows: poor (AUC < 0.8), fair (0.8 < AUC < 0.9), good (0.9 < AUC < 0.95), and very good (0.95 < AUC ≤ 1.0) (Adhikari et al. 2023). To evaluate the model's performance, in addition to AUC, the use of TSS is recommended. The TSS score ranges from -1 to 1 and is categorized as follows: poor (-1 to 0.4), fair (0.4 to 0.5), good (0.5 to 0.7), very good (0.7 to 0.85), excellent (0.85 to 0.9), and perfect (0.9 to 1) (Lobo et al. 2008; Wang et al. 2024). Validation relied on the average AUC and the True Skill Statistic (TSS), calculated as TSS=(sensitivity+specificity) −1 (Allouche et al. 2006). These metrics provided a robust assessment of the model's predictive accuracy and suitability.

Mapping and suitable area calculation

The MaxEnt output was evaluated and analyzed using ArcGIS (version 10.8.2) to visualize and interpret the potential invasion areas for *A. riparia*. Potentially suitable areas were identified by delineating regions at risk of future invasion based on MaxEnt predictions, highlighting locations where the species may expand under projected climate conditions.

RESULTS AND DISCUSSION

Model performance and variable contribution in the present scenario

The habitat suitability model for *A. riparia* indicated that suitable habitats in Mizoram to be primarily distributed in the middle (1500-1700 m) to higher altitudes (up to 2055 m), particularly in Eastern to South-Eastern regions of Mizoram (Figure 3.A). The analysis highlighted that areas within the elevational range of 680-2000 m are highly susceptible to invasion by *A. riparia*, with a maximum occurrence probability of 0.98. Validation through present climatic scenarios, including the ROC curve and jackknife of regularized training gain, confirmed these findings (Figures 3.B-C).

The model demonstrated strong performance, achieving a True Skill Statistic (TSS) value of 0.768 and an Area Under the Curve (AUC) score of 0.977, indicating high predictive accuracy (Table 3). The temperature annual range (BIO7) emerged as the most influential variable, contributing 61.5% to the model, followed by the highest temperature of the warmest month (BIO5, 11.2%) and precipitation seasonality (BIO15, 6.1%). The warmest quarter precipitation (BIO18) contributed the least at 0.3%. Consistent with these findings, the jackknife test highlighted that the highest training gain and AUC value were driven by the annual temperature range (BIO7), highlighting its importance in the current spatial distribution of *A. riparia* in Mizoram.

Table 2. Potential suitable habitats in Mizoram, India vulnerable to invasion by *Ageratina riparia*

Districts	**Areas vulnerable to *A. riparia* invasion**
Champhai	Selam, Ngopa, Vapar, Murlen National Park
Hnahthial	Thiltlang, Hnahthial, Darzo
Khawzawl	Zuchhip
Lawngltai	Sangau, S. Vanlaiphai, Vathuampui, Phawngpui National Park, Cheural
Lunglei	Serkawn, Lunglei,
Saiha	Chakhang, Zawngling
Serchiip	N. Vanlaiphai

Table 3. Prediction outcomes of *Ageratina riparia* habitat suitability modelling

	Prediction parameters	**Current**	**2050**			**2070**		
			RCP26	**RCP45**	**RCP85**	**RCP26**	**RCP45**	**RCP85**
Ageratina riparia	AUC	0.977	0.981	0.977	0.988	0.975	0.987	0.991
	TSS	0.768	0.618	0.766	0.746	0.839	0.851	0.709
	Code	**BIO7**	**BIO2**	**BIO2**	**BIO2**	**ELEV**	**BIO14**	**BIO2**
	Percentage of contribution	61.5%	28.8%	52.7%	32.2%	58.6%	38%	28.1%
	Code	**BIO7**	**BIO2**	**BIO2**	**ELEV**	**BIO5**	**ELEV**	**ELEV**
	Permutation of importance	55.3	44.2	26.6	30.5	22	34.4	31.9
	Percentage of suitable habitat	4.78	4.92	6.09	2.31	6.23	3.65	1.78

Note: *****Percentage of contribution & Permutation of importance at 10th percentile training presence threshold

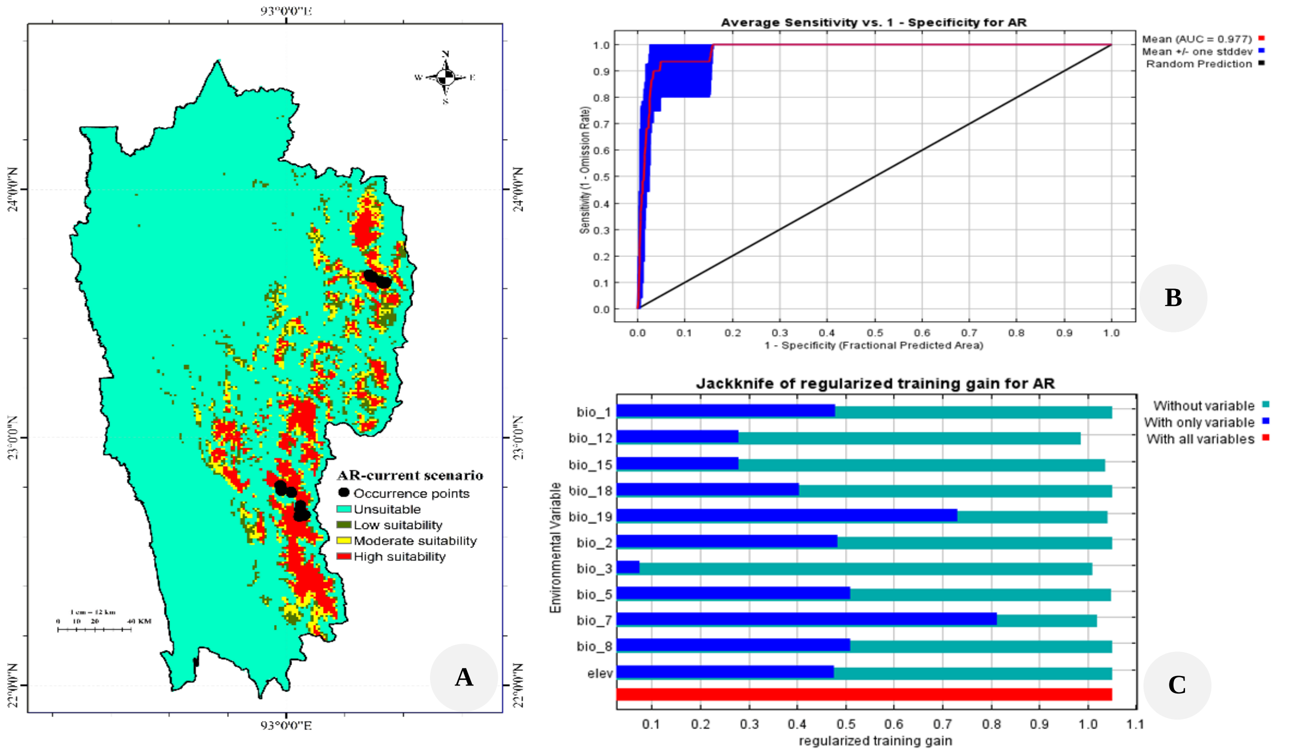

Figure 3. A. The present potential suitability invasion distribution of *A. riparia* in Mizoram, India under current climatic conditions; B. The present ROC curve under current climatic conditions of *A. riparia* in Mizoram; C. The Jackknife of regularized training gain under current climatic conditions of *A. riparia* in Mizoram

Present potential distribution

The potential invasion distribution of *A. riparia* showed relatively low suitability in Mizoram under current climatic conditions. Only 4.78% (1007.95 km²) of the area in Mizoram is suitable to varying degrees (from low to high suitability) for invasion by *A. riparia* (Figure 3.A and Table 3). Nearly seven districts in Mizoram, with limited areas at elevations ranging from 1500 to 1835 m.a.s.l., exhibited high suitability for *A. riparia* invasion based on climatic factors. Forested regions in Sangau, Hnahthial, Darzo, South Vanlaiphai, Thaltlang, and Sentetfiang, situated in the eastern to southern parts of the state, showed vulnerability to *A. riparia* invasion, particularly in the middle to upper elevational zones. In southern Mizoram, the most suitable habitats included the natural forests of Hnahthial, Sangau, and Hmunlai. High-altitude areas of Mizoram (above 1750 m), such as South Vanlaiphai and Darzo, also demonstrated higher suitability for invasion, a trend that aligned with field observations. The natural forest areas within the boundaries of protected areas like Murlen National Park, Phawngpui National Park, and parts of Lengteng Wildlife Sanctuary exhibited the highest percentage of suitable area for *A. riparia* invasion (Figure 3 and Table 2).

Future invasion risk and change in habitat suitability

The habitat modelling outcomes projected the most climatically favorable areas for *A. riparia* invasion in Mizoram. These results indicated that the risk of invasion would increase under the RCP 2.6 climate scenario for 2050 and 2070. Significant risks of invasion were anticipated for 2070, with a growth of 1.45% under RCP 2.6, and for 2050, with a growth of 1.31% under RCP 4.5. Increased invasion risk was projected in the southeastern regions of the state, including areas such as Serchhip, Lunglei, Lawngtlai, South Vanlaiphai, Darzo, Sangau, and Hnahthial, where suitable habitats are expected to expand.

Shifting from RCP 4.5 to RCP 8.5 is projected to decrease climatically suitable areas for *A. riparia* invasion in 2050 and 2070 (Figures 4 and 5; Table 3). While the projections under the extreme climate scenario (RCP 8.5) show a reduction in suitable areas, an expansion in the upper elevational range is expected for both 2050 and 2070 (Figures 4 and 5). Conversely, under the moderate emission scenario of RCP 4.5, the model predicts a contraction in the upper elevational range for these years (Figures 4 and 5).

With changing climatic conditions, all geographical regions in Mizoram, except the highest mountainous areas, are expected to experience an increase in climatically suitable zones for *A. riparia*. Although a slight decrease in suitable areas is projected for the mid-mountain region, it is anticipated to remain the most favorable for *A. riparia* invasion, followed by shifting cultivation fields and fallow lands at mid-altitudes across all future climate scenarios (Table 3). Under the four future climate scenarios—RCP 2.6 for 2050 and 2070, and RCP 4.5 for 2050 and 2070—the central and eastern regions of Mizoram are projected to experience the greatest increase in climatically suitable areas, followed by southern Mizoram. However, under the RCP 8.5 scenario for 2050 and 2070, the central and northwestern parts of Mizoram are expected to lose all suitable areas for *A. riparia* invasion.

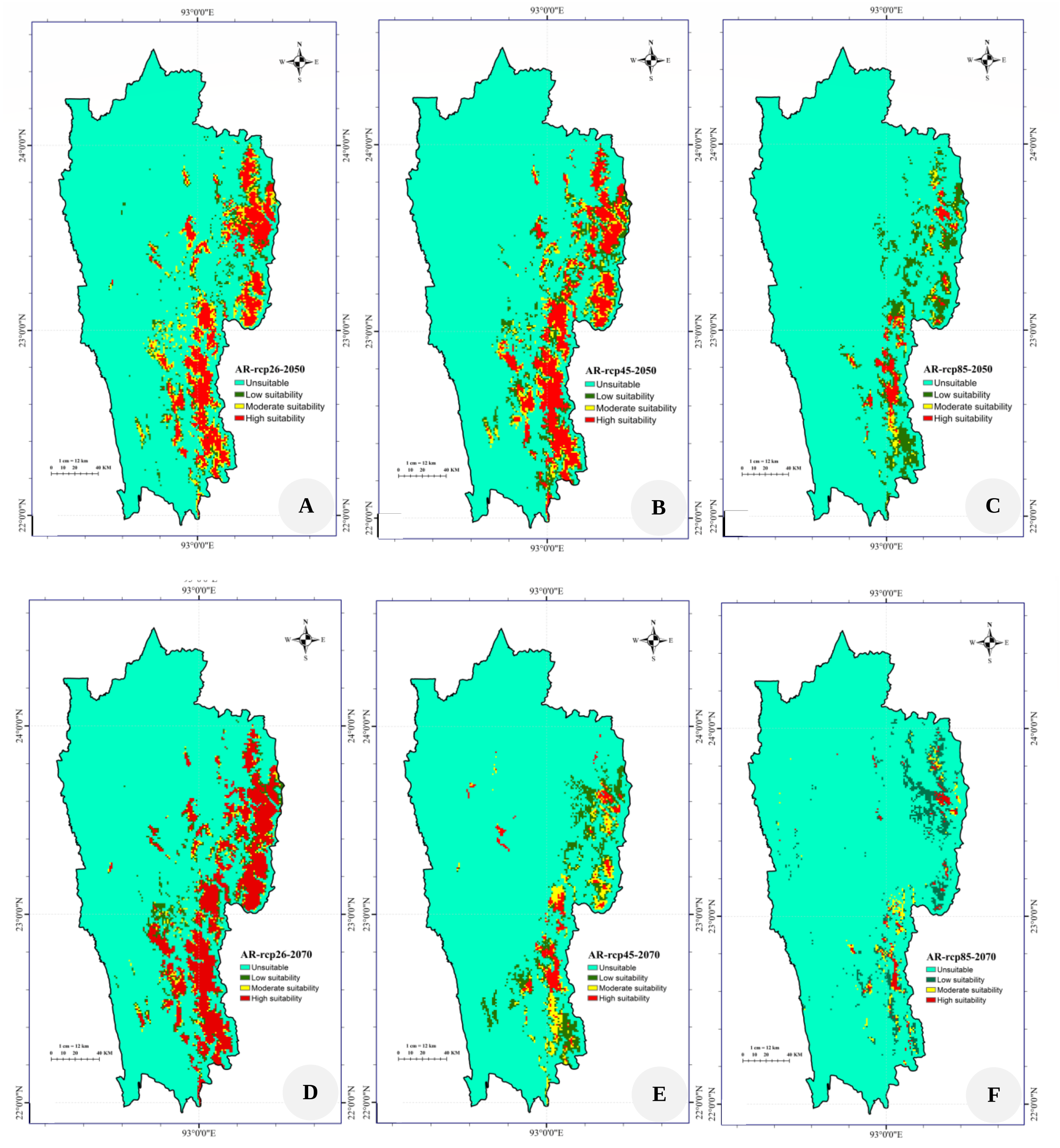

Figure 4. Potential distribution of *Ageratina riparia* under future climate in the Year 2050 in A. RCP 2.6; B. RCP 4.5; C. RCP 8.5 and under future climate: Year 2070 in D. RCP 2.6; E. RCP 4.5; F. RCP 8.5

Additionally, under RCP 4.5 and RCP 8.5 scenarios for 2050 and 2070, climatically suitable areas in southern Mizoram, particularly around Siaha and the western parts of Lawngtlai district, are projected to decline. According to future climate projections under RCP 2.6, RCP 4.5, and RCP 8.5 for 2050 and 2070, protected areas such as Phawngpui National Park and Murlen National Park are also at risk of *A. riparia* invasion (Figures 4 and 5). If the current invasion trend continues, these projections suggest high suitability for invasion in Murlen National Park, Phawngpui National Park, Lengteng Wildlife Sanctuary, and surrounding areas.

Under current climate conditions, the highest controlling factors for *A. riparia* invasion are BIO7 (annual temperature range) and BIO19 (rainfall of the coldest quarter) (Figure 3). Altitude, BIO2 (mean diurnal range), and BIO14 (rainfall of the driest month) significantly influence the future projections of *A. riparia* invasion. Additionally, BIO7 was found to have the highest independent training gain (Figure 5).

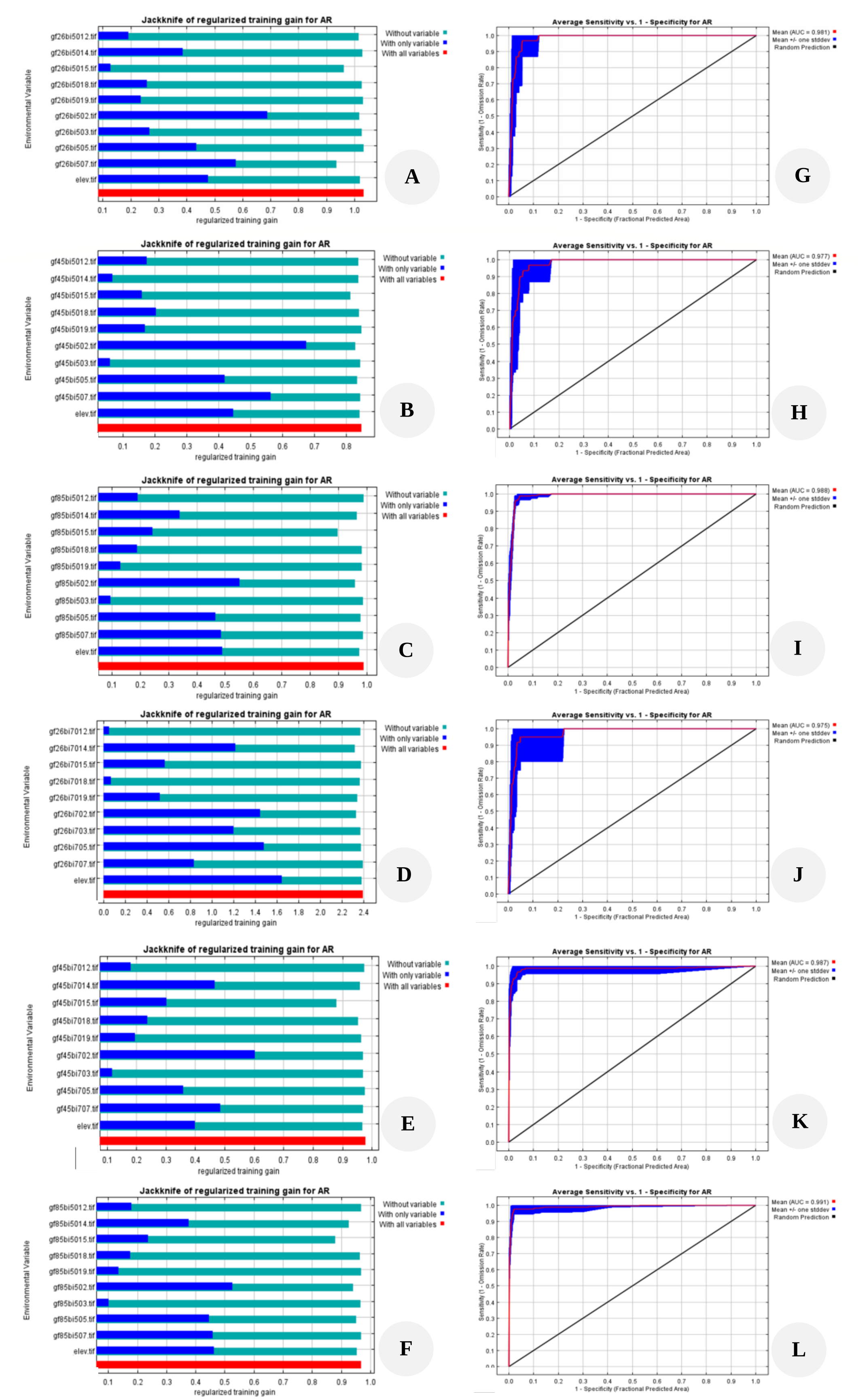

Figure 5. Jackknife & ROC curve of *Ageratina riparia* under future climate in the year 2050: RCP 2.6, A. Jackknife and G. ROC curve; RCP 4.5, B. Jackknife and H. ROC curve; RCP 8.5, C. Jackknife and I. ROC curve and under future climate in the year 2070: RCP 2.6, D. Jackknife and J. ROC curve; RCP 4.5, E. Jackknife and K. ROC curve; RCP 8.5, F. Jackknife and L. ROC curve

Discussion

Neo-invasive Invasive Alien Plant species (IAPs) such as *A. riparia* have caused significant economic damage and pose a global threat to biodiversity (Changjun et al. 2021). Seebens et al. (2017) projected that the cumulative presence of IAPs on continents will increase by 36% from the present scenario to 2050. Identifying invasion hotspots through habitat suitability modelling is the most effective damage control strategy to mitigate invasion by IAPs (Fournier et al. 2019). While *A. riparia* has limited occurrence in Mizoram, its impact remains concerning (Sengupta and Dash 2020), necessitating management under both current and future climate change scenarios to mitigate its detrimental effects on natural forests in the region. Historical herbarium records indicate that *A. riparia,* native to Mexico, was introduced to India as an ornamental plant at the Calcutta Botanical Gardens in 1901, now known as Acharya Jagadish Chandra Bose Indian Botanic Garden (Calcutta, 05.03.1901, G.J. Lane Esgre, CAL0000204374).

The current potential habitat distribution of *A. riparia* aligns closely with existing occurrence records used in the model analysis (Figure 2), supporting the findings of Fang et al. (2021) and Li et al. (2022). These studies reported that invasive species distributions in China are highly concentrated in regions like Yunnan and coastal provinces, while western areas, such as the Tibetan Plateau, exhibit the least. Our models yielded AUC values above 0.91, indicating excellent results and confirming the robustness of the habitat suitability models in this study (Adhikari et al. 2023).

Climatic variables, such as the mean diurnal range (BIO2), annual temperature range (BIO7), and precipitation during the driest month (BIO14), alongside topographical variables like elevation, were found to be the most influential factors in projecting the future distribution of *A. riparia* in Mizoram. In China, similar climatic factors, including precipitation, temperature, and elevation, have been reported to influence the invasion of an allied species, *A. adenophora* (Xian et al. 2022). Anthropogenic disturbances and population density also correlate strongly with invasive species richness in neighboring countries like China (Yang et al. 2017) and Nepal (Shrestha et al. 2015). In India, the same patterns have been observed in the Central Himalayas (Bhattarai et al. 2014) and the Western Himalayas (Lamsal et al. 2018), highlighting anthropogenic disturbances as key factors in the spread of IAPs. The optimum growth of *A. riparia* occurs in temperatures ranging from 15-30°C, with seasonality in rainfall, as shown by the response curves. This finding is consistent with research conducted in other subtropical regions such as southwest China (Li et al. 2022) and Nepal (Poudel et al. 2020) for other Asteraceae invasive species.

This study provides the first-ever habitat distribution modelling for *A. riparia*. During field surveys in Mizoram, *A. riparia* was found to have a restricted distribution, mostly in disturbed landscapes in Eastern and Southern Mizoram. The habitat suitability modelling, which utilized uncorrelated climatic variables, showed similar trends, predicting that only higher altitudes will be vulnerable to *A. riparia* invasion, influenced by high precipitation, temperature variation, moderate annual temperature, and various anthropogenic disturbances. Pure patches of *A. riparia* were observed in areas such as Hnahthial, Vapar, Murlen, Sangau, and Thaltlang, primarily at middle to upper altitudes. Light exposure and temperature variation were found to be important factors influencing the occurrence of *A. riparia*, similar to observations in Meghalaya at mid-altitudes (around 1500 m; Tripathi et al. 2012). The changes in the suitable habitat areas were less than 15%, with most areas remaining stable for *A. riparia* invasion (Table 3). In particular, the habitat of *A. riparia* is expected to shift gradually toward the extreme Southern and Eastern parts, including Phawngpui National Park and Murlen National Park. This habitat shift mirrors the findings of Goncalves et al. (2014), who described the proliferation of *L. camara* in India, reflecting the multidirectional risk of future invasions. Such habitat shifts may also be attributed to phenotypic plasticity, which enables species to dominate native species in the same region (Li et al. 2022), allowing *A. riparia* to migrate into favorable climatic regions for rapid invasion.

While bioclimatic variables are crucial, land-use changes, forest clearing for increased sunlight exposure, soil conditions, and escalating anthropogenic disturbances also influence the distribution of invasive species in Mizoram. These species have spread to abandoned fallow lands, urban environments, and roadside habitats (Adhikari et al. 2023; Sengupta and Dash 2023b).

There is growing evidence that climate change will likely increase the risk of plant invasions, creating more suitable areas in the future (Adhikari et al. 2023). This study's results project that climate change will lead to an increase in suitable areas for *A. riparia* invasion. The species is expected to expand its habitat under six future climate scenarios: RCP 2.6 (2050 and 2070), RCP 4.5 (2050 and 2070), and RCP 8.5 (2050 and 2070). Similar projections have been made in various regions in India, showing the expansion of climatically suitable areas for Asteraceae invasives under future climate scenarios (Adhikari et al. 2015; Datta et al. 2019), and in neighboring countries (Poudel et al. 2020; Xian et al. 2022). Some projections suggest a gradual decline in climate suitability after reaching peak levels (Fandohan et al. 2015), a trend also observed in the suitability models under the RCP 8.5 scenario for 2050 and 2070. These findings suggest that while climate-driven increases in suitability are apparent, they may be influenced by other complex factors.

The use of noxious IAPs for bioprospecting could be an effective management strategy for *A. riparia* invasion in Mizoram (Sengupta and Dash 2023a). This study provides essential insights into potential invasion hotspots for A. riparia, offering a crucial database for developing long-term, scientifically informed management strategies. Sustainable practices such as regulated traditional slash-and-burn cultivation, strict quarantine protocols for food crop imports, and controlled introductions of exotic plants should be prioritized to strengthen these efforts. Sengupta and Dash (2023a) have highlighted the ethnobotanical uses of *A. riparia* in Mizoram, noting that an infusion made from dried leaves and capitula (8-10 dried capitula per 100 ml) is traditionally used as an herbal remedy for hypertension and diabetes. Additionally, the plant collected from Mizoram has high proximate values and mineral content, indicating its potential as a bioprospecting resource for the local community. Inhabitants of Vapar and Sangau also use the plant to create partitions between lands and gardens or reinforce embankments.

Establishing a control and management framework for IAPs in Mizoram's natural forests is critical. Effective control strategies for *A. riparia* should include (i) Ecological restoration of invaded ecosystems by promoting dominant native plant species capable of outcompeting invasives, (ii) Mechanical control methods combined with crop competition techniques in disturbed areas near national parks, and (iii) Using the cut-root-stock method alongside the introduction of native fast-growing grasses and legumes. Awareness programs and workshops should be organized in affected areas to educate villagers, local forest departments, and students about the impact of IAPs and sustainable control and management practices.

In conclusion, this study presents the first state-level modelling of habitat suitability for *A. riparia* in Mizoram, marking an initial effort in North-East India to assess the potential invasion of this neo-invasive species. The predicted habitat distribution aligns with the global spread of various Asteraceae invaders and highlights key invasion hotspots for *A. riparia* within Mizoram. The modelling results indicate that large areas of Mizoram, including its natural forests, exhibit favorable climatic conditions conducive to the acclimatization and potential spread of *A. riparia*. However, despite the identified suitability, the expansion of this Invasive Alien Plants (IAPs) remains within a controllable stage in many regions, particularly in certain parts of the state. Effective management of this invasion requires continuous monitoring, as changing climatic and anthropogenic conditions could facilitate the spread of *A. riparia* into newly suitable areas. Notably, the current model does not account for potential changes in anthropogenic disturbances, which may further exacerbate the risk of invasion. The study successfully identifies the primary invasion hotspots based on the current distribution of *A. riparia*, providing valuable insights into regions at risk of future invasion. This information, when combined with additional ecological data, such as the presence of vulnerable ecosystems and biodiversity hotspots, can help prioritize areas for targeted management. Preventing the spread of *A. riparia* through early intervention is more cost-effective and sustainable than undertaking eradication efforts after the species has already proliferated. Therefore, proactive management strategies, including strengthening oversight of anthropogenic disturbances and promoting ecological restoration, are critical for mitigating the future impact of *A. riparia* on Mizoram's natural forests.

ACKNOWLEDGEMENTS

The authors are grateful to Dr A.A. Mao, Director, Botanical Survey of India, and Kolkata, India, for their encouragement and facilities. They also express their gratitude to the Department of Environment, Forest & Climate Change, Government of Mizoram, India, for granting permission to survey and conduct this study.

REFERENCES

Adhikari D, Tiwary R, Barik SK. 2015. Modeling hotspots for invasive alien plants in India. PloS one 10 (7): e0134665. DOI: 10.1371/journal.pone.0134665.

Adhikari P, Lee YH, Poudel A, Hong SH, Park YS. 2023. Global spatial distribution of *Chromolaena odorata* habitat under climate change: random forest modeling of one of the 100 worst invasive alien species. Sci Rep 13: 9745. DOI: 10.1038/s41598-023-36358-z.

Ahmed DA, Hudgins EJ, Cuthbert RN, Haubrock PJ, Renault D, Bonnaud E, Courchamp F. 2022. Modeling the damage costs of invasive alien species. Biological Invasions 24: 1949-1972. DOI: 10.1007/s10530-021-02586-5.

Allouche O, Tsoar A, Kadmon R. 2006. Assessing the accuracy of species distribution models: Prevalence kappa and the True Skill Statistic (TSS). J Appl Ecol 43 (6): 1223-1232. DOI: 10.1111/j.1365-2664.2006.01214.x.

Bhattarai KR, Måren IE, Subedi SC. 2014. Biodiversity and invasibility: Distribution patterns of invasive plant species in the Himalayas, Nepal. J Mount Sci 11: 688-696. DOI: 10.1007/s11629-013-2821-3.

Boral D, Moktan S. 2022. Mapping the spatial distribution of the invasive Mexican Sunflower *Tithonia diversifolia* (Asteraceae) in South East Asia. J Asia-Pac Biodivers 15 (3): 425-434. DOI: 10.1016/j.japb.2022.03.006.

Botella C, Joly A, Monestiez P, Bonnet P, Munoz F. 2020. Bias in presence-only niche models related to sampling effort and species niches: Lessons for background point selection. PLoS One 15 (5): e0232078. DOI: 10.1371/journal.pone.0232078.

Brown JL, Bennett JR, French CM. 2017. SDMtoolbox 2.0: The next generation Python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. PeerJ 5: e4095. DOI: 10.7717/peerj.4095.

Changjun G, Yanli T, Linshan L, Bo W, Yili Z, Haibin Y, Bohao C. 2021. Predicting the potential global distribution of *Ageratina adenophora* under current and future climate change scenarios. Ecol Evol 11 (17): 12092-12113. DOI: 10.1002/ece3.7974.

Choudhury MR, Deb P, Singha H, Chakdar B, Medhi M. 2016. Predicting the probable distribution and threat of invasive *Mimosa diplotricha* Suavalle and *Mikania micrantha* Kunth in a protected tropical grassland. Ecol Eng 97: 23-31. DOI: 10.1016/j.ecoleng.2016.07.018.

Datta A, Schweiger O, Kühn I. 2019. Niche expansion of the invasive plant species *Ageratina adenophora* despite evolutionary constraints. J Biogeogr 46 (7): 1306-1315. DOI: 10.1111/jbi.13579.

Essl F, Lenzner B, Bacher S et al. 2020. Drivers of future alien species impacts: An expert-based assessment. Glob Chang Biol 26 (9): 4880-4893. DOI: 10.1111/gcb.15199.

Fandohan AB, Oduor AM, Sodé AI, Wu L, Cuni-Sanchez A, Assédé E, Gouwakinnou GN. 2015. Modeling vulnerability of protected areas to invasion by *Chromolaena odorata* under current and future climates. Ecosyst Health Sustain 1 (6): 11878996. DOI: 10.1890/EHS15-0003.1.

Fang Y, Zhang X, Wei H, Wang D, Chen R, Wang L, Gu W. 2021. Predicting the invasive trend of exotic plants in China based on the ensemble model under climate change: A case for three invasive plants of Asteraceae. Sci Total Environ 756: 143841. DOI: 10.1016/j.scitotenv.2020.143841.

Forest Survey of India (FSI). 2021. State of Forest Report Ministry of Environment Forest and Climate Change, Dehradun. https://fsi.nic.in/forest-report-2021-details.

Fournier A, Penone C, Pennino MG, Courchamp F. 2019. Predicting future invaders and future invasions. Proc Natl Acad Sci 116 (16): 7905-7910. DOI: 10.1073/pnas.1803456116.

Goncalves E, Herrera I, Duarte M, Bustamante RO, Lampo M, Velasquez G, Sharma GP, García-Rangel S. 2014. Global invasion of *Lantana camara*: Has the climatic niche been conserved across continents? PLoS One 9 (10): e111468. DOI: 10.1371/journal.pone.0111468.

Griffies SM, Winton M, Donner LJ et al. 2011. The GFDL CM3 coupled climate model: Characteristics of the ocean and sea ice simulations. J Clim 24 (13): 3520-3544. DOI: 10.1175/2011JCLI3964.1.

Hautier Y, Tilman D, Isbell F, Seabloom EW, Borer ET, Reich PB. 2015. Anthropogenic environmental changes affect ecosystem stability via biodiversity. Science 348 (6232): 336-340. DOI: 10.1126/science.aaa1788.

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. 2005. Very high-resolution interpolated climate surfaces for global land areas. Intl J Climatol 25 (15): 1965-1978. DOI: 10.1002/joc.1276.

Lamsal P, Kumar L, Aryal A, Atreya K. 2018. Invasive alien plant species dynamics in the Himalayan region under climate change. Ambio 47 (6): 697-710. DOI: 10.1007/s13280-018-1017-z.

Li Y, Song T, Lai Y, Huang Y, Fang L, Chang J. 2022. Status, mechanism, suitable distribution areas and protection countermeasure of invasive species in the karst areas of Southwest China. Front Environ Sci 10: 957216. DOI: 10.3389/fenvs.2022.957216.

Mačić V, Albano PG, Almpanidou V et al. 2018. Biological invasions in conservation planning: A global systematic review. Front Mar Sci 5: 178. DOI: 10.3389/fmars.2018.00178.

Merow C, Bois ST, Allen JM, Xie Y, Silander Jr JA. 2017. Climate change both facilitates and inhibits invasive plant ranges in New England. Proc Natl Acad Sci 114 (16): e3276-e3284. DOI: 10.1073/pnas.1609633114.

Mushtaq S, Reshi ZA, Shah MA, Charles B. 2021. Modelled distribution of an invasive alien plant species differs at different spatiotemporal scales under changing climate: A case study of *Parthenium hysterophorus* L. Trop Ecol 62 (3): 398-417. DOI: 10.1007/s42965-020-00135-0.

Phillips SJ, Anderson RP, Dudík M, Schapire RE, Blair ME. 2017. Opening the black box: An open-source release of MaxEnt. Ecography 40 (7): 887-893. DOI: 10.1111/ecog.03049.

Phillips SJ, Dudík M. 2008. Modeling of species distributions with MaxEnt: New extensions and a comprehensive evaluation. Ecography 31 (2): 161-175. DOI: 10.1111/j.0906-7590.2008.5203.x.

Poudel AS, Shrestha BB, Joshi MD, Muniappan R, Adiga A, Venkatramanan S, Jha PK. 2020. Predicting the current and future distribution of the invasive weed *Ageratina adenophora* in the Chitwan–Annapurna Landscape Nepal. Mount Res Dev 40 (2): R61. DOI: 10.1659/MRD-JOURNAL-D-19-00069.1.

Rameshprabu N, Swamy PS. 2015. Prediction of environmental suitability for invasion of *Mikania micrantha* in India by species distribution modeling. J Environ Biol 36 (3) : 565-570.

Ray D, Behera MD, Jacob J. 2019. Comparing invasiveness of native and non-native species under changing climate in North-East India: Ecological niche modeling with plant types differing in biogeographic origin. Environ Monit Assess 191: 793. DOI: 10.1007/s10661-019-7685-8.

Richardson DM, Rejmánek M. 2011. Trees and shrubs as invasive alien species–a global review. Divers Distrib 17 (5): 788-809. DOI: 10.1111/j.1472-4642.2011.00782.x.

Saranya KRL, Lakshmi TV, Reddy CS. 2021. Predicting the potential sites of *Chromolaena odorata* and *Lantana camara* in forest landscape of Eastern Ghats using habitat suitability models. Ecol Inf 66: 101455. DOI: 10.1016/j.ecoinf.2021.101455.

Seebens H, Blackburn TM, Dyer EE et al. 2017. No saturation in the accumulation of alien species worldwide. Nat Commun 8: 14435. DOI: 10.1038/ncomms14435.

Sengupta R, Dash SS. 2020. Invasion status of three non-native species from family Asteraceae in Mizoram. Nelumbo 62 (1): 27-39. DOI: 10.20324/nelumbo/v62/2020/153742.

Sengupta R, Dash SS. 2023a. Ecological impact of alien plant invasion in national parks of an Indo-Burma biodiversity hotspot in India. J Agric Ecol 15: 109-124. DOI: DOI: 10.58628/JAE-2315-119.

Sengupta R, Dash SS. 2023b. Predicting the potential invasion hotspots of *Chromolaena odorata* under current and future climate change scenarios in heterogeneous ecological landscapes of Mizoram India. Res Ecol 5(4): 1-12. DOI: 10.30564/re.v5i4.5920.

Shrestha BB, Shabbir A, Adkins S W. 2015. *Parthenium hysterophorus* in Nepal: a review of its weed status and possibilities for management. Weed Res 55 (2): 132-144. DOI: 10.1111/wre.12133.

Tererai F, Wood AR. 2014. On the present and potential distribution of *Ageratina adenophora* (Asteraceae) in South Africa. S Afr J Bot 95: 152-158. DOI: 10.1016/j.sajb.2014.09.001.

Thapa S, Chitale V, Rijal SJ, Bisht N, Shrestha BB. 2018. Understanding the dynamics in distribution of invasive alien plant species under predicted climate change in Western Himalaya. PloS one 13 (4): e0195752. DOI: 10.1371/journal.pone.0195752.

Tiwari S, Mishra SN, Kumar D, Kumar B, Vaidya SN, Ghosh BG, Rahaman SM, Khatun M, Garai S, Kumar A. 2022. Modelling the potential risk zone of *Lantana camara* invasion and response to climate change in eastern India. Ecol Process 11: 10. DOI: 10.1186/s13717-021-00354-w.

Tripathi RS, Yadav AS, Kushwaha SPS. 2012. Biology of *Chromolaena odorata*, *Ageratina adenophora* and *Ageratina riparia*: A review Invasive alien plants. An ecological appraisal of Indian Subcontinent 32: 43-56, Springer. DOI: 10.1079/9781845939076.0043.

Valavi R, Guillera-Arroita G, Lahoz-Monfort JJ, Elith J. 2022. Predictive performance of presence-only species distribution models: A benchmark study with reproducible code. Ecol Monogr 92 (1): e01486. DOI: 10.1002/ecm.1486.

Vaz AS, Alcaraz-Segura D, Campos JC, Vicente JR, Honrado JP. 2018. Managing plant invasions through the lens of remote sensing: A review of progress and the way forward. Sci Total Environ 642: 1328-1339. DOI: 10.1016/j.scitotenv.2018.06.134.

Vilà M, Basnou C, Pyšek P et al. 2010. How well do we understand the impacts of alien species on ecosystem services? A pan-European cross-taxa assessment. Front Ecol Environ 8 (3): 135-144. DOI: 10.1890/080083.

Xian X, Zhao H, Wang R, Zhang H, Chen B, Huang H, Liu W, Wan F. 2022. Predicting the potential geographical distribution of *Ageratina adenophora* in China using equilibrium occurrence data and ensemble model. Front Ecol Evol 10: 973371. DOI: 10.3389/fevo.2022.973371.

Yang G, Gui F, Liu W, Wan F. 2017. Crofton weed *Ageratina adenophora* Sprengel. In: Wan F, Jiang M, Zhan A (eds). Biological Invasions and Its Management in China. Springer, Singapore. DOI: 10.1007/978-981-10-3427-5_8.