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ARTICLE

Predicting the Potential Invasion Hotspots of *Chromolaena odorata* under Current and Future Climate Change Scenarios in Heterogeneous Ecological Landscapes of Mizoram, India

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ABSTRACT

Recent trends in globalization, human mobility surge and global trade aggravated the expansion of alien species introduction leading to invasion by alien plants compounded by climate change. The ability to predict the spread of invasive species within the context of climate change holds significance for accurately identifying vulnerable regions and formulating strategies to contain their wide proliferation and invasion. Anthropogenic activities and recent climate change scenarios increased the risk of *Chromolaena odorata* invasion and habitat expansion in Mizoram. To forecast its current distribution and habitat suitability amidst climatic alterations in Mizoram, a MaxEnt-driven habitat suitability model was deployed using the default parameters. The resultant model exhibited that the current spatial range of *C. odorata* occupies 15.37% of geographical areas deemed suitable for varying degrees of invasion. Projections for 2050 and 2070 anticipated an expansion of suitable habitats up to 34.37% of the geographical area of Mizoram, specifically under RCP 2.6 in 2070 in comparison with its present distribution. Currently, the distributional range of *C. odorata* in Mizoram spans from lower (450 m) to mid elevational ranges up to 1700 meters, with limited presence at higher altitudes. However, the habitat suitability model extrapolates that climate changes will elevate the invasion risk posed by *C. odorata* across Mizoram, particularly in the North-Western and Central regions. The projection of further territorial expansion and an upward shift in altitudinal range in the future underscores the urgency of instating robust management measures to pre-empt the impact of *C. odorata* invasion. This study recommends the imperative nature of effective *C. odorata* management, particularly during the initial stages of invasion.

Keywords: Climate change; Niche modelling; Habitat suitability; Biodiversity hotspots; Plant invasion; Maxent

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1. Introduction

Invasive alien plants (hereafter IAPs) are perceived as one of the most significant contributors to global environmental transformation [1] leading to an aggravated threat to biodiversity, ecosystem function and services [2]. Richardson and Rejmánek [3] predicted that global climate change scenarios will subsequently accelerate invasion scenarios in natural forests and the combined impact of anthropogenic activities as well as global climate change play pivotal roles in the global expansion of invasion by alien plants [4]. However, comprehending the intricate invasion dynamics between climate change and IAPs remains elusive due to their complex interactions [5]. Primary challenges within the realm of biological invasion research encompass the invasive nature of alien species, the susceptibility of habitats to invasion, the impact of invasiveness, the anticipation of invasive tendencies, and the management of invasion in natural forest areas [6]. The first fundamental three constitute the major focal points in the study of biological invasion, and a profound comprehension of these aspects provides a robust scope to effectively manage biological invasions [7]. Ultimately, the prime objective of biological invasion research is to control and manage biological invasions [8]. An effective strategy to obviate the further spread of IAPs involves examining present and future spatial patterns of potential invasive alien plants (IAPs) habitats [9]. Recent studies have undertaken analyses of plausible shifts in IAPs distributions under diverse climate change scenarios, encompassing regional [10] and global [11] scales. Leveraging species distribution models (SDMs), these studies have facilitated the early detection of hotspots for invasion by alien plants [10,8,12] through mapping potential IAPs ranges and quantifying correlations between the noxious IAPs and environmental factors based on present occurrence data and species habitat conditions (e.g., temperature, precipitation, topography etc.).

Chromolaena odorata, a perennial shrub belonging to the Asteraceae family, naturally occurs within the tropical and subtropical zones of Central and South America, encompassing regions like Mexico, Brazil and the Caribbean [13]. This plant, transitioning from herbaceous to woody, is capable of attaining a height of up to 2 meters. Its propagation occurs via both vegetative and sexual means, exhibiting significant fecundity and rapid germination rates [14]. Notably versatile, *C. odorata* can thrive across diverse soil types, spanning from sandy dunes to dense clays, and its seeds possess the ability to endure in the soil for as long as 6 years [13]. Tolerant to soils ranging from acidic to neutral, this plant establishes itself proficiently in disturbed terrains, grasslands, forests, and fallow areas. Owing to its capacity for both short and long-distance dispersion, *C. odorata* has earned recognition among the world's 100 worst invasive alien species [13]. Originating as an ornamental plant introduced to India in the 1800s, *C. odorata* extended its presence to South East Asia by 1920, carried by contaminated pasture and forest seeds [14].

In the context of invasion scenarios, *C. odorata* represents a formidable weed, causing serious concerns to the natural forests and agricultural fields in Mizoram [15]. These IAPs have invaded ubiquitously in abandoned shifting cultivation lands, natural forests, roadsides and forest trek paths; impacting the native flora of Mizoram [15].

Mitigating the invasion by noxious IAPs into new and potentially favourable natural forest areas is widely considered the ideal strategy for restricting ecological and economic impacts [9]. Species distribution modelling (SDM) plays a pivotal role in assessing risks and facilitating conservation [10]. Various modelling techniques are available for such predictions [16,17]. The MaxEnt model was selected for this study due to its demonstrated capability in forecasting species distributions and its superior performance relative to other presence-only SDMs [18]. In this context, it is pertinent to mention that no previous studies were performed in Mizoram to estimate the future invasion scenario. To fulfil the research gap, the invasion and establishment scenarios of *Chromolaena odorata* in the natural forests of Mizoram were determined in this study with the utilization of MaxEnt model [16] of ENM (ecological niche modelling) or habitat suitability approach. The outcomes of this research will effectively address the primary research goal—identifying the potential suitable invasion hotspots for *Chromolaena odorata* in Mizoram, an Indo-Burma biodiversity hotspot based on its present distribution in Mizoram. Subsequently, the outcomes could be useful for versatile applications, including identifying additional locations for invasion by the IAPs, identifying sites prone to future proliferation and in conjunction with additional data such as the distribution of vulnerable ecosystems or biodiversity hotspots, selecting regions of priority for management.

2. Materials and methods

2.1 Study sites

The present study was conducted in Mizoram, a part of Indo-Burma biodiversity hotspot (**Figure 1**) and carried out from July, 2018 to September, 2021 for floristic as well as ecological surveys including protected areas. Only 6.75% of the geographical area of the state comes under protected area networks. The temperature range during the March-May (summer) stays around 18-29 °C whereas during August-December (winter) low temperature range (11-24 °C) persists. The rainfall profile exhibits annual rainfall of 2160 mm to 3500 mm [19].

2.2 Species occurrence data

The species occurrence data for *Chromolaena odorata* was collected through field investigation during the floristic and ecological surveys. The occurrence co-ordinates were recorded using Garmin Montana 680. All the occurrence points were embedded in the digital elevation map of the study area featured in **Figure 1** and scanned to remove duplicates as well as any erroneous records outside the study area followed by a reduction in sampling bias with the thinning distance set to 1 km (30 arc seconds) using ArcGIS tool (ArcMap 10.8.2).

2.3 Environmental variables

Environmental variables (**Table 1**) and elevation data for the current and future climate conditions were sourced from the World-Clim database [20]. The current climate data were obtained from the World-Clim database version 2.0 at ~1 km^2 (30 arc second) resolution. In the case of future climate change predictions, the nineteen bioclimatic variables were obtained for RCP 2.6, RCP 4.5, and RCP 8.5 for the year 2050 and the year 2070 based on the global climatic model GFDL-CM3 (CMIP5) [21]. The obtained data were clipped based on the Mizoram area and subsequently converted to the ASCII format. Only the uncorrelated bioclimatic variables were retained for running the MaxEnt algorithm.

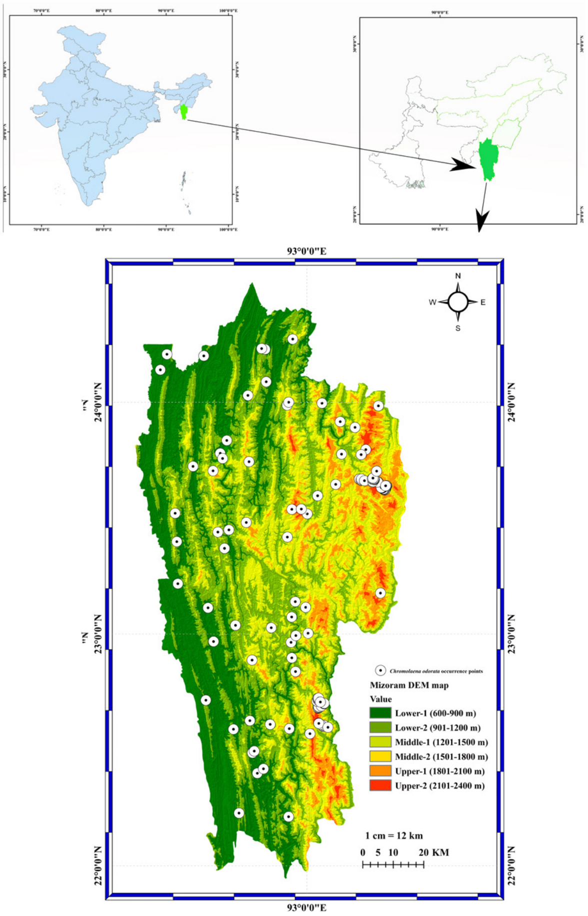

Figure 1. Digital elevation map of Mizoram with present occurrence point of *C. odorata*.

2.4 Modelling procedure

The habitat suitability modelling was performed using MaxEnt algorithm version 3.4.4 [22]. The modelling algorithm was run with only the uncorrelated

9 bioclimatic variables (**Table 1**) for auto features, excluding the hinge feature and setting the 10-percentile training presence threshold rule along with 10 times replication. SDM toolbox 2.0 was used to perform a multi-collinearity test to eliminate the highly correlated variables ($r > 0.9$) [23]. The models were generated using a 30% random test percentage (Thapa et al., 2018). For future climate predictions, the models were projected on future climate layers for RCP 2.6, RCP 4.5, and RCP 8.5 for both years 2050 and 2070 using the uncorrelated bioclimatic variables. The model validation was assessed using the average AUC (area under the curve) values and true skill statistic (TSS = (sensitivity + specificity) − 1) [24].

2.5 Mapping and suitable area calculation

The output mapping from MaxEnt was prepared in the ArcGIS software. Subsequently, corresponding 10th percentile training presence was set as the threshold in order to remove areas with low probability of occurrence of the generated maps for each model [25] and the most suitable areas for invasion threat were calculated from the generated maps.

Table 1. Uncorrelated variables used for *Chromolaena odorata* habitat suitability modelling.

Abbreviation code	Variable name
BIO1	Annual mean temperature
BIO2	Mean diurnal range (Mean of monthly (max temp – min temp))
BIO4	Temperature seasonality (standard deviation * 100)
BIO7	Temperature annual range (BIO5-BIO6)
BIO8	Mean temperature of wettest quarter
BIO12	Annual precipitation
BIO14	Precipitation of driest month
BIO17	Precipitation of driest quarter
Elev	Elevation profile

3. Results

3.1 Model performance and variable contribution in the present scenario

Figure 2A exhibits the current suitable habitat of *Chromolaena odorata* in Mizoram. The present habitat of the noxious invasive species in the present model covers mostly the lower elevational range areas in Mizoram and high invasion suitability was observed in north-western Mizoram. The highest probability of occurrence exhibited by the model was 0.98. ROC curve and jackknife of regularized training gain under current climatic scenarios were shown in **Figures 2A and 2B**.

The present model for *Chromolaena odorata* exhibited better performance in comparison to the random, with a mean training AUC value of 0.917 and a TSS value of 0.763 (**Table 2**). Amongst the 9 predictor variables used for the model preparation, the major (51.3%) contributor was annual Precipitation (BIO12) followed by annual mean temperature (BIO1, 16.7%) and precipitation of driest month (BIO14, 15.3%). Temperature Annual Range (BIO7) exhibited the lowest (0.1%) contribution. Maxent's jackknife test of regularized training gain for the climatic variables also exhibited that annual Precipitation (BIO12) had the highest AUC and training gain.

3.2 Present potential distribution

Currently, 15.37% (3241.07 km^2) area of the total geographic area of Mizoram is suitable in varied degrees (low to high) for *C. odorata* (**Figure 2**; **Table 2**). The majority of the districts of Mizoram with an elevational range of 435-1625 m.a.s.l. exhibited climatic suitability for the invasion of *C. odorata*. The most climatically suitable areas for this weed were exhibited in the middle elevational region of Mizoram in areas like Kolasib, Mamit, Aizawl and Dawrlawn along Central to Northern parts of the state. The most suitable habitats in southern Mizoram were Thenzawl, Lawngtlai, Aibawk, Sangau and Hmunlai. Eastern Mizoram areas were low to moderate suitable for invasion by *C. odorata* in areas like Champhai, Hnahlan, Murlen, Vapar, Selam and Ngopa. Higher elevational areas (above 1700 m) exhibit less suitability for invasion by *C. odorata*. As the middle mountain elevation exhibited maximum suitability to the noxious weed, the potential threat to the protected natural forest areas in the region

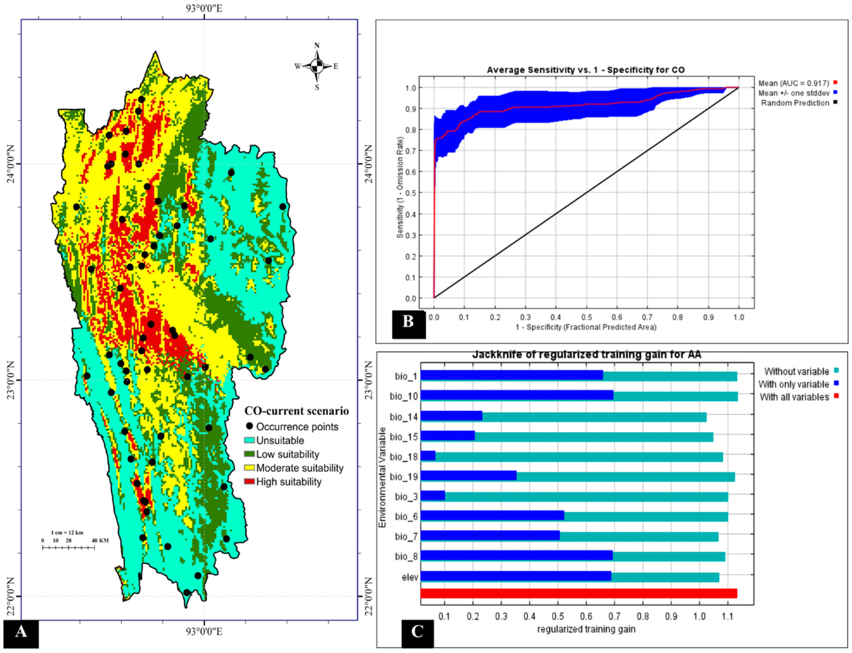

Figure 2. (A). Potential distribution of *Chromolaena odorata*; (B). ROC curve and (C). Jackknife of regularized training gain under current climate uncorrelated variables. [CO = *Chromolaena odorata*]

Table 2. Prediction outcomes of *Chromolaena odorata* habitat suitability modelling.

Prediction parameters	**Present scenario**	**2050**			**2070**		
		RCP26	**RCP45**	**RCP85**	**RCP26**	**RCP45**	**RCP85**
AUC	0.917	0.953	0.952	0.951	0.953	0.954	0.948
TSS	0.763	0.768	0.782	0.756	0.722	0.747	0.766
Code	**BIO12**	**BIO14**	**BIO14**	**BIO01**	**BIO14**	**BIO01**	**BIO14**
Percentage of contribution	51.3%	50.6%	34%	28.1%	41.9%	25.3%	25.9%
Code	**BIO12**	**BIO14**	**BIO1**	**BIO1**	**BIO1**	**BIO1**	**BIO14**
Permutation of importance	26	42.8	25.3	40.3	28.4	51.4	28.3
Percentage of suitable habitat	15.37	17.21	21.71	12.85	25.38	25.14	11.82
Suitable habitat (km^2)	3241.07	3629.07	4577.98	2709.67	5351.88	5301.27	2492.48

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

was also evaluated. Among the protected areas in Mizoram-Dampa Wildlife Sanctuary, Thorangtlang Wildlife Sanctuary, Pualrang Wildlife Sanctuary, Ngengpui Wildlife Sanctuary and lower altitudes of Lengteng Wildlife Sanctuary, Murlen National Park and Phawngpui National Park were within the moderate to high percentage of suitable area for invasion by *C. odorata* (**Figure 2**).

3.3 Future invasion risk and change in habitat suitability

The projected climatically favourable regions for *C. odorata* are expected to expand when considering the RCP 2.6 scenario for both 2050 and 2070. In contrast, for RCP 4.5, the years 2050 and 2070 demonstrate even greater suitability, as indicated in **Figure 3** and **Table 2**. The most substantial increase in suitable habitat area were anticipated for 2070, with a growth of 10.05% under RCP 2.6 and 9.77% under RCP 4.5. These suitable habitat expansions were particularly observed in greater probability in Kolasib, Mamit, Aizawl, Lunglei, Lawngtlai, and Serchhip districts in Mizoram.

However, transitioning from RCP 4.5 to 8.5

would result in a reduction of climatically suitable areas for the *C. odorata* invasion in both 2050 and 2070 (**Figure 3**; **Table 2**). Despite the reduction in suitable areas under extreme climate conditions (RCP 8.5), the upper elevational range is predicted to expand in 2050 and 2070 (**Figure 5**). In contrast, under the moderate emission scenario of RCP 4.5, the model anticipates a contraction in the upper elevational limit for both years 2050 and 2070. Nonetheless, the lower elevation limit of *C. odorata* is projected to either remain stable or increase in future climate scenarios (**Figure 5**).

With shifting climatic conditions, it is expected that all geographical regions, except the highest mountainous region, will gain climatically suitable areas. Although a minor decline in suitable areas is projected for the mid-mountain region, it will still harbour the most favourable areas for the weed, followed by the low mountain and agricultural fields across all future climate scenarios (**Table 2**). Across four future climate scenarios—RCP 2.6 in 2050 and 2070, and RCP 4.5 in 2050 and 2070—the central

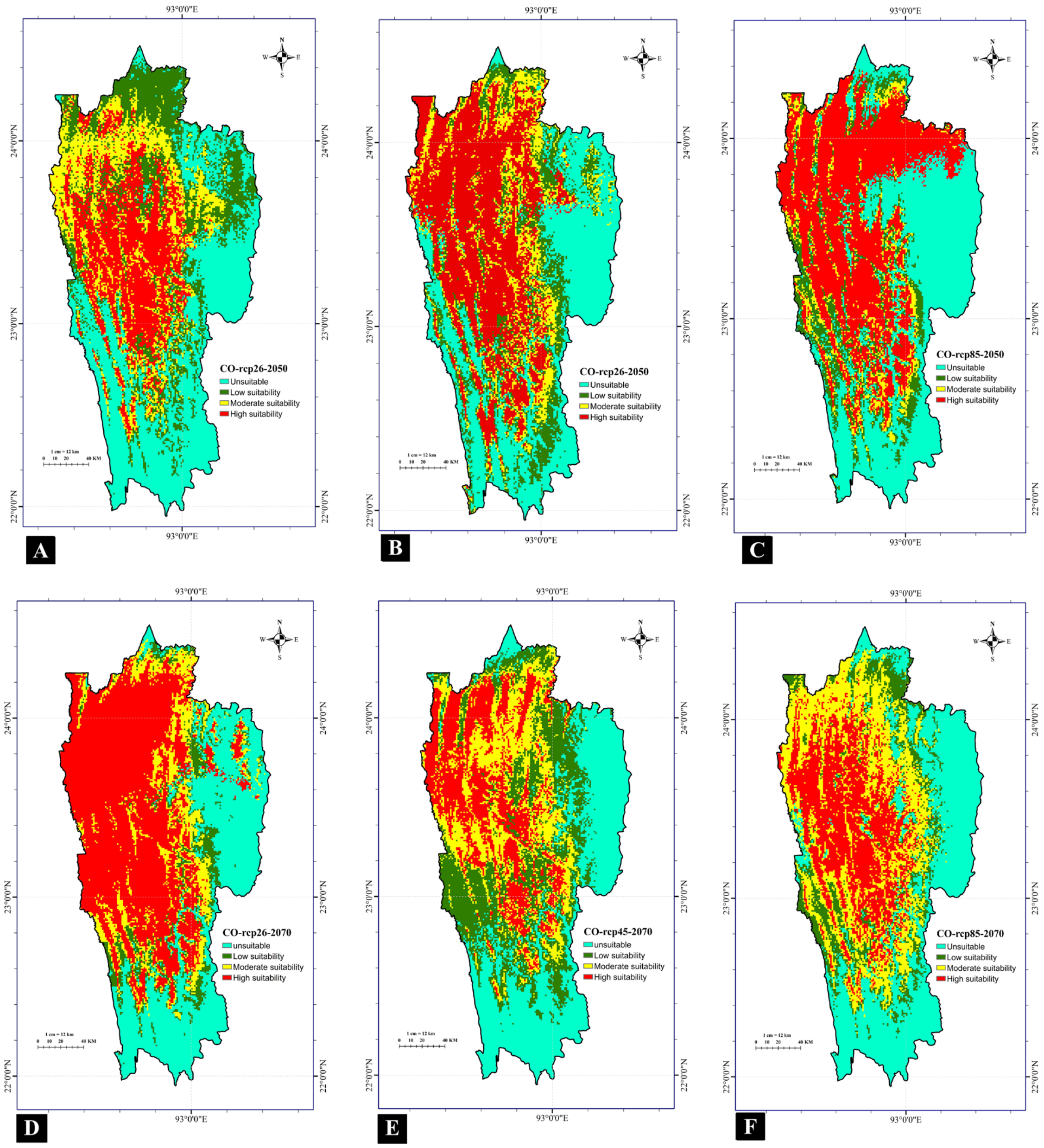

Figure 3. Potential distribution of *Chromolaena odorata* under future climate: Year 2050 in (A). RCP 2.6, (B). RCP 4.5, (C). RCP 8.5 and Year 2070 in (D). RCP 2.6, (E). RCP 4.5, (F). RCP 8.5. [CO = *Chromolaena odorata*]

region of Mizoram was exhibited to experience the greatest increase in climatically suitable areas. However, under RCP 8.5 for 2050 and 2070, the eastern part of Mizoram will completely lose all the suitable areas for *C. odorata* invasion.

Additionally, in the context of RCP 4.5 and 8.5 for both 2050 and 2070, the suitable areas in Southern Mizoram were projected to decrease, particularly near Siaha and the southern sections of the Lawngtlai district. Among all geographical regions, under RCP 2.6, 4.5, and 8.5 for both 2050 and 2070, the protected areas that will experience the greatest expansion in suitable areas are Dampa Tiger Reserve, Pualrang Wildlife Sanctuary, Ngengpui Wildlife Sanctuary, and Thorangtlang Wildlife Sanctuary (**Figure 3**). As observed under current climatic conditions, Dampa Tiger Reserve was anticipated to gain more suitable areas than other protected areas in Mizoram in future climate scenarios (**Figure 4**). Furthermore, under RCP 2.6, 4.5 and 8.5. for both 2050 and 2070, two national parks in Mizoram i.e., Murlen National Park and Phawngpui National Park will be climatically less suitable or completely unsuitable areas for invasion by *C. odorata*.

The climatic variables, highlighting the suitable habitats for *C. odorata* in the present-day scenario, the variable BIO12 (Annual Precipitation) exhibited the highest percentage of contribution at 51.3%. Similarly, for all the six future models, the highest percentage of contribution was shown by BIO14 (Precipitation of Driest Month) and BIO1 (Annual Mean Temperature). From the jackknife of the current model (**Figure 2C**), it was observed that BIO12 possess the maximum training gain when used independently. Similarly, the jackknife and ROC curve for 2050 under three RCPs was depicted in **Figure 4** whereas the jackknife and ROC curve for 2070 under three RCPs was depicted in **Figure 5**.

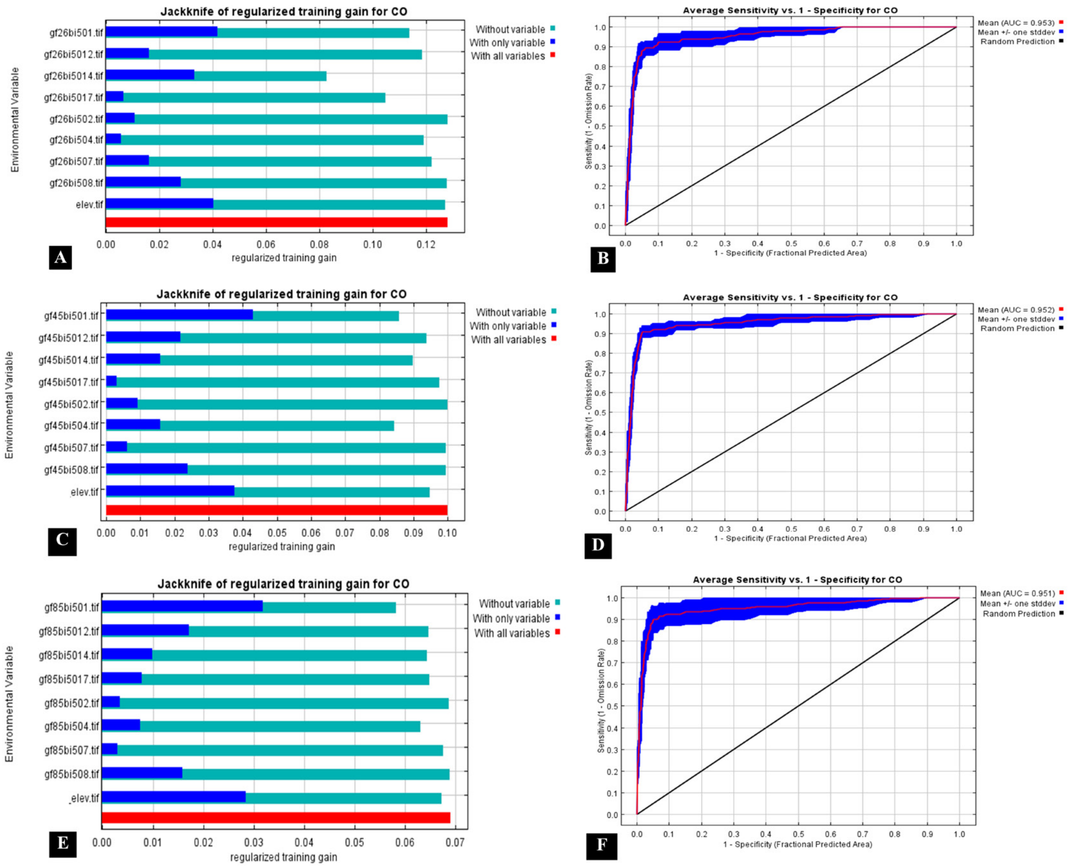

Figure 4. Jackknife & ROC curve of *Chromolaena odorata* under future climate in the year 2050: RCP 2.6, (A) Jackknife and (B) ROC curve; RCP 4.5, (C) Jackknife and (D) ROC curve year 2070; RCP 8.5, (E) Jackknife and (F) ROC curve. [CO = *Chromolaena odorata*]

4. Discussion

Climatic elements like temperature and precipitation exert significant influence in determining the pathways and achievements of plant invasions [26]. The results of the study interpreted that the annual mean temperature (BIO1) and annual precipitation (BIO12) influence the distribution of *C. odorata* invasion in current and future scenarios. This correlation was in congruence with findings from other researchers [13,23]. Similarly, invasion and occurrence probability by this noxious weed reduces when the mean temperature dips lower temperatures during winter (Jackknife graphs, **Figure 4**). This implies the occurrence of the noxious invasive in middle mountain zones in Mizoram where its upper distribution limit is restricted by temperature and elevation. Similar observations were also made in Doon Valley in the middle elevation [27].

In this study, habitat suitability modelling was performed with both complete and spatially rarefied occurrence points to mitigate errors and overfitting due to spatial correlation. The model based on spatially rarefied points showcased superior performance in terms of AUC and TSS scores (**Table 2**) representing the accuracy. Outcomes of this predictive model offer accurate predictions and simulations of the invasion distribution of *C. odorata* spread in Mizoram for both current and future scenarios. The distribution and modelling of invasive species are shaped by both intrinsic factors like dispersal and species generation rates, and extrinsic factors like anthropogenic activities. According to the Jackknife test in our study, temperature-related variables (BIO1, BIO4 and BIO7) and precipitation-related variables (BIO12 and BIO17) significantly influenced *C. odorata* habitat suitability (**Figure 1**). Similar findings were reported by habitat suitability modelling in the global model [23]. *C. odorata* usually grows well in warm, wet conditions, avoiding frost [13] but is vulnerable to extremely cold temperatures and excessively dry soil. Therefore, it is predicted to flourish

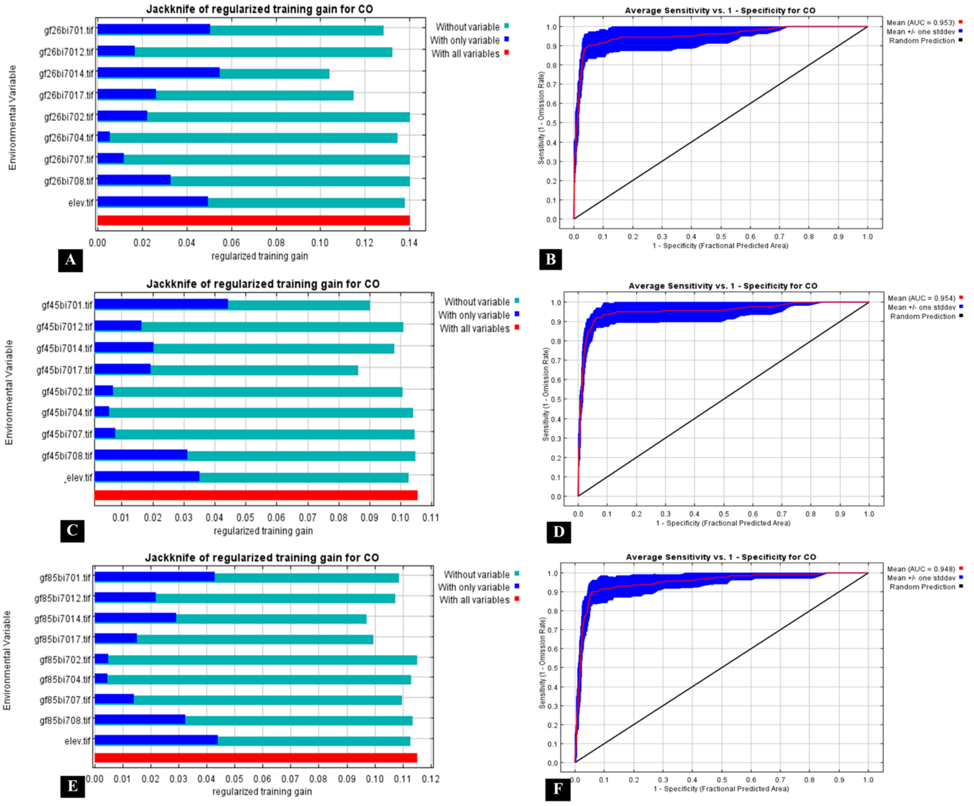

Figure 5. Jackknife & ROC curve of *Chromolaena odorata* under future climate in the year 2070: RCP 2.6, (A) Jackknife and (B) ROC curve; RCP 4.5, (C) Jackknife and (D) ROC curve year 2070; RCP 8.5, (E) Jackknife and (F) ROC curve.

with changing climate patterns where mean temperature would increase [23]. While bioclimatic variables play a pivotal role, other factors like land use changes, soil, and increasing anthropogenic disturbances also influence the distribution of the invasive species in Mizoram spreading in abandoned fallow lands, urban environments and roadside habitats [15].

Results of the study identify the most suitable habitat range of *C. odorata* near north-western and central Mizoram primarily in humid tropical, subtropical, and warm temperate climatic regions. Expansion is projected in central pockets of western and northern Mizoram. However, based on the outcome of predictive models, the habitats in southern and eastern Mizoram were observed as unsuitable in the future near the high altitudes.

There is growing evidence that climate change is likely to increase the risk of plant invasions, creating more suitable areas in the future [28]. Results of this study also showed similar projections that with changing climate, there will be an increase in suitable areas for *C. odorata* invasion in the future. The noxious invasive would obtain a gain in suitable areas in 6 future climate scenarios: RCP 2.6 (2050 and 2070), RCP 4.5 (2050 and 2070) and RCP 8.5 (2050 and 2070). The results of this study illustrate that shifting climatic conditions are projected to enhance the suitability of areas for *C. odorata* invasion in the future.

Similar trends were anticipated in various regions in India, reporting the expansion of climatically fitting regions for *C. odorata* under future climate scenarios [25,29-31]. Nevertheless, some projections also highlight a gradual decline in climate suitability subsequent to reaching peak suitability [32] which was also observed in southern and eastern areas of Mizoram in this study. Such findings indicate that while climate-induced suitability increases are plausible, they might be influenced by intricate trajectories in different contexts. Subsequently, *C. odorata* expands its range across India, including North-Eastern regions, owing to a blend of anthropogenic activities such as international trade, tourism, transportation, and shifts in land usage. Natural phenomena like winds, tides, surface runoff, and the movement of animals have also contributed to its dissemination. This expansion of favourable areas can be attributed to inherent and adaptively augmented eco-physiological tolerances of *C. odorata* regulating its growth in the face of heightened temperature concentrations [33].

5. Conclusions

C. odorata exhibits a potential to acclimate to the changing climate conditions, including escalated temperatures and shifting precipitation patterns. This investigation harnessed a habitat suitability model approach to project the spatial distribution of *C. odorata* and distinguish the invasion hotspots for elevated vulnerability to invasion under both present circumstances and future climate scenarios. The outcomes unveiled that between 2023 and 2070, *C. odorata* will continue to expand the prevailing ecological niche while concurrently extending its territory across central and north-western Mizoram. On the contrary, the suitable habitats will reduce in southern and eastern parts of the state. The outcome of this investigation identifies the regions that might evolve into suitable habitats in light of current and anticipated climate changes, thereby furnishing valuable insights for formulating enduring management tactics concerning *C. odorata*. Immediate control and management measures such as mechanical intervention, biological control, and reinstating native flora are imperative in areas of Mizoram at higher risk, especially the protected natural forests. Local communities in Mizoram use *C. odorata* for various socio-economic purposes including bio-manure and first aid which can be incorporated as control methods to employ management of the invasive plant. Precautions should be taken to prevent seed dispersal and vegetative regeneration of the plant in fallow areas. However, for regions like central Mizoram and protected areas like wildlife sanctuaries, national parks at future risk of invasion, an integrated weed management approach should be implemented for effective management options. By identifying areas that are potentially at risk in the future, our study constitutes a helpful resource for local stakeholders and policymakers to take appropriate and timely action to minimize the risk of invasion by *C. odorata* associated with climate change.

Author Contributions

RS (Ph.D. student and first author) contributed to the plant sample collection, identification, field work, Maxent and data analysis of the data and drafted the paper. SSD contributed to the validation of the data, methodology preparation and contributed to critical reading of the manuscript. All the authors have read the final manuscript and approved the submission.

Conflict of Interest

The authors express no conflict of interest.

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