

Ensemble modelling to assess the dynamics of invasive plant species under changing climate in Bagmati Province, Nepal

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Abstract. Shrestha M, Baral S, Shrestha UB, Kunwar RM. 2025. Ensemble modelling to assess the dynamics of invasive plant species under changing climate in Bagmati Province, Nepal. *Biodiversitas* 26: 2589-2600. Invasive Alien Plant species (IAPs) present a significant threat to biodiversity, particularly under changing climatic conditions. This study investigates the distribution patterns of three IAPs, viz. *Ageratina adenophora*, *Chromolaena odorata*, and *Lantana camara*, within Bagmati Province, Nepal, under both current and projected climate scenarios (SSP245 and SSP585). Using species occurrence data from field surveys, available secondary data, and eight bioclimatic variables, we applied an ensemble modelling approach across twelve Global Circulation Models (GCMs). The findings reveal that, under present conditions, *A. adenophora* occupies the most extensive suitable area (4,121.6 km²), whereas *C. odorata* occupies the least (1,964.07 km²). Future projections indicate an increase in habitat suitability for all three IAPs in future climates. Specifically, under SSP245, *L. camara* shows a 12.4% rise in suitable habitat area during the period 2021-2040, with *C. odorata* showing a 15.6% increase during 2041-2060. Under SSP585, the suitability of *L. camara* is projected to increase substantially by 37.2% and 40.7% in the periods 2021-2040 and 2041-2060, respectively. This highlights the more conducive environment created by climate change for IAPs in the future. The models demonstrate higher suitability in the middle mountain regions and a decline in suitability with increasing elevation. Specifically, *C. odorata* favors tropical zones, and *A. adenophora* and *L. camara* thrive in subtropical regions. These IAPs pose the greatest risks to cropland and forest ecosystems, adversely affecting local economies and biodiversity. The high-performance metrics of the models (AUC: 0.85-0.92, TSS: 0.51-0.67) confirm their reliability, with Precipitation of Driest Month (BIO14) being the most significant variable under current climate conditions and Mean Diurnal Range (BIO2) emerging as critical for future climate scenarios. These results emphasize the need for proactive site-specific management strategies to mitigate the impacts of IAPs under climate change.

Keywords: Climate change, ensemble modelling, invasive alien plant species, SSP245, SSP585

INTRODUCTION

Invasive Alien Plant species (IAPs) are among the five main drivers of change in nature, together with changes in land and sea use, direct exploitation of organisms, pollution, and climate change (IPBES 2019). Worldwide, there are 1,061 IAPs of which 6% are recognized as invasive (IPBES 2023). The global distribution of IAPs is heavily influenced by trade and transportation networks, which facilitate their spread across regions (Seebens et al. 2017; van Kleunen et al. 2019). Their further spread is influenced not only by environmental factors such as temperature, precipitation, and road density, but also by some characteristics of the invasive plants themselves (Thapa et al. 2018; Rai and Singh 2020; Oh et al. 2021). Global climate change is a major driver of the proliferation of invasive species, as it can alter the habitat suitable for a species and thus encourage the spread and establishment of IAPs in new ecosystems (Bellard et al. 2016; Dullinger et al. 2017). IAPs are generalists that can tolerate a wide range of climates and thus can adapt and expand into new areas when the climate alters (Kariyawasam et al. 2019).

Changes in biotic interactions due to altered climate may accelerate the process of benign non-native species becoming invasive (Early et al. 2016).

In Nepal, 182 alien flowering plant species have become naturalized, out of which 29 are identified as IAPs (Sharma et al. 2020; Shrestha and Shrestha 2021; Shrestha et al. 2021). Only two decades ago, no more than 16 species of IAPs were reported (Tiwari et al. 2005). Climate change further accelerated their spread across Nepal, especially in central Nepal (Shrestha and Shrestha 2019), and impacted local biodiversity, ecosystem functioning, and livelihoods negatively (Adhikari et al. 2019). Thus, the rapid rise in the number of invasive species and their distribution in Nepal are issues of concern.

IAPs pose a significant environmental challenge in Bagmati Province, one of Nepal's seven provinces. The present study deals with three problematic IAPs in Bagmati Province: *Lantana camara*, *Chromolaena odorata*, and *Ageratina adenophora*, which have been reported to pose major ecological and economic threats. *Lantana camara* and *C. odorata* are ranked among the 100 worst invasive species in the world, and *A. adenophora* poses one of the

most serious problems in Nepal (Everard et al. 2018). Local stakeholders expressed concerns about these species, leading to recent recommendations for more focused studies on them (Everard et al. 2018). They inhibit forest regeneration, decrease native biodiversity, and lead to a decline in ecosystem functions (Shrestha et al. 2017; et al. 2019).

Accurate modelling and forecasting of the spreading potential of these IAPs under both present and future climatic conditions are therefore essential. This can be achieved by an ensemble modelling approach, combining the output of several models to gain accuracy in predicting spread events, as shown in studies of species distributions by Kotu and Deshpande (2015), Zurell et al. (2016) and Ramirez-Reyes et al. (2021). Better prediction will help in the identification of vulnerable areas, prioritization of conservation efforts, and formulation of early detection and rapid response strategies (Hernandez et al. 2022). Knowledge of the future distribution of IAPs is also critical for climate adaptation since climate change may alter suitable habitats of species, potentially hastening their spread and changing local distribution patterns (Dullinger et al. 2017; Bellard et al. 2018). The inclusion of climate change factors in the distribution models will enable authorities and conservationists to anticipate and manage the impacts of IAPs more effectively, enhancing their response strategies (Seebens et al. 2017; Finch et al. 2021).

This study aims to identify areas with the highest probability of occurrence of *L. camara*, *C. odorata*, and *A. adenophora* in Bagmati Province under current and future

climatic conditions, and to evaluate how climate change may alter their potential distribution.

MATERIALS AND METHODS

Study area

This study was conducted in Bagmati Province, located in the central part of the Nepal (Figure 1). Bagmati Province covers an area of about 20,300 km², which is roughly 13.79% of the total land area of Nepal. It has 13 districts, representing four of the country's five physiographic regions, namely Siwalik, Middle Mountain, High Mountain, and High Himal. Siwalik consists of flat lands with tropical and subtropical climates, while Middle Mountain encompasses hilly terrain with sub-tropical to temperate climates. High Mountain and High Himal represent areas with temperate and alpine climates, respectively. The province comprises varied climates because of its diversified topography and altitude, which ranges from 141 m at Golaghat in Chitwan District to 7,422 m at Ganesh Himal. This supports a range of ecosystems, such as the deciduous, coniferous, and alpine forests and woodlands that cover 27.29% of the area (National Statistics Office 2024). Annual precipitation is highly variable in the province, ranging between 150-200 mm in the high Himalayas to 1,100-3,000 mm in the southern plains (National Statistics Office 2024). Similarly, the average temperature varies between -10°C and 30°C annually in the province (National Statistics Office 2024).

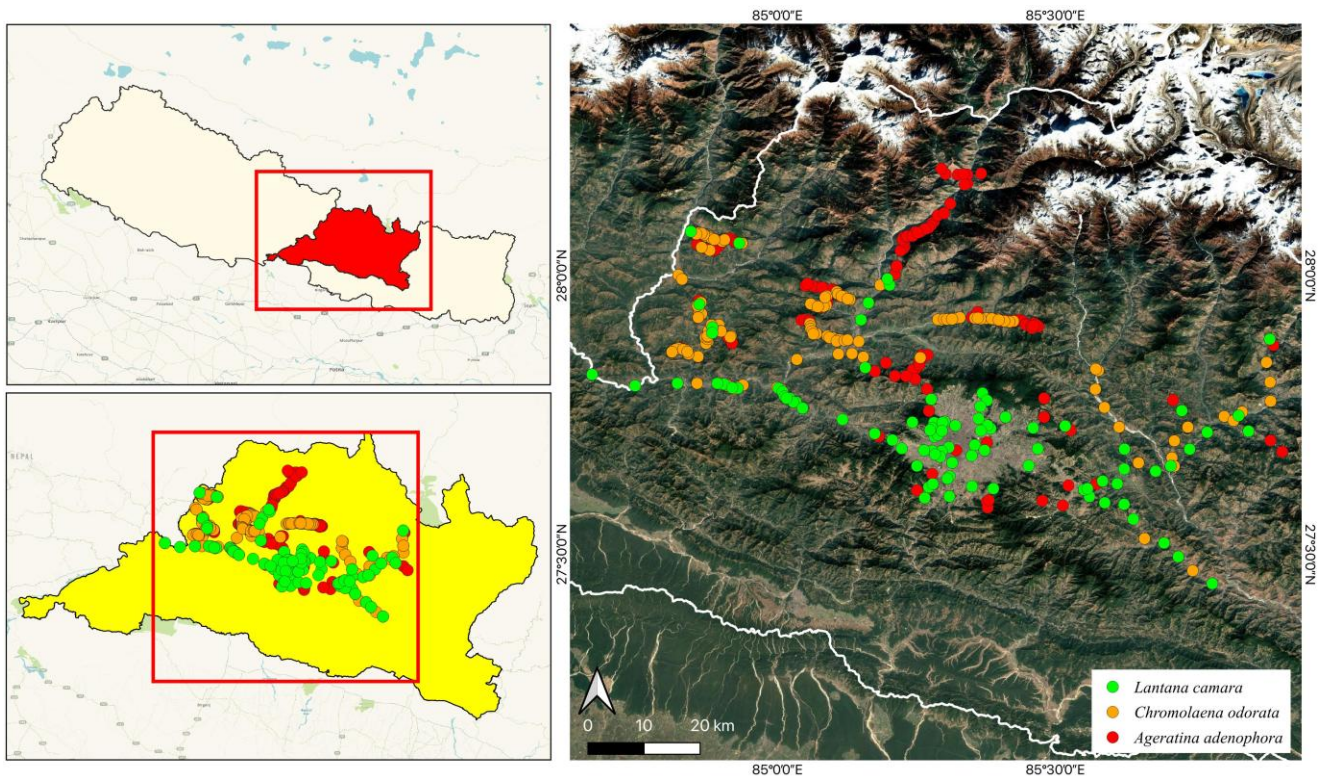


Figure 1. Study area showing the occurrence of three invasive alien plant species in Bagmati Province, Nepal

The distribution of IAPs in different regions of Nepal varies widely. Some areas harbor invasive species more than others; for example, western Nepal has less area of IAPs compared to the central and eastern regions (Shrestha et al. 2017). The central region is a hotspot for IAPs with vast areas of habitat suitable for all studied species (Shrestha et al. 2018). However, recent research by Shrestha and Shrestha (2019) has shown a reduction in potential areas of IAPs in Bagmati Province under future climate scenarios. The province has been chosen for further analysis, with the main ecological zones having different land use types and different climatic zones prone to the colonization of invasive species. The zones were selected based on criteria such as the level of ecological importance, biodiversity, and their susceptibility to introduced species' establishment and spread, among others.

Data collection

Occurrence data

Out of the 13 districts in Bagmati Province, occurrence points were collected from nine districts: Kathmandu, Bhaktapur, Lalitpur, Dhading, Nuwakot, Rasuwa, Kavrepalanchowk, Sindhupalchowk, and Chitwan. Although we randomly selected the occurrence points, we purposely avoided choosing points within a 500 m radius. During field visits in July, August, and September of 2023, we collected 122 occurrence points of *A. adenophora*, 93 of *C. odorata*, and 52 of *L. camara*. We also extracted 140 occurrence points for *A. adenophora*, 68 for *C. odorata*, and 46 for *L. camara* from secondary sources (Shrestha et al. 2023) to meet our need for a considerable amount of data for modelling.

Spatial filtering of the presence points was performed using R software version 4.3.2 to align spatial resolution with environmental variables. In the filtering, only one presence point was retained per 30-arc-sec grid (1×1 km), and redundant points were removed (Elith et al. 2010). For example, in modelling the distribution of *A. adenophora*, only 201 presence points out of a total of 263 were used (Table 1). This approach improves model performance, handles spatial autocorrelation, and addresses possible overfitting problems (Boria et al. 2014).

Environmental variables

A total of 19 bioclimatic variables under current climate conditions (1970–2000) and two shared socioeconomic pathway scenarios: SSP245 and SSP585 for the next two

20-year periods (2021–2040 and 2041–2060) were downloaded from WorldClim (accessed December 2023) with a spatial resolution of 30 arc seconds (~1×1 km). The SSP245 is the most plausible because it projects warming of 3°C above pre-industrial levels by the end of the century, whereas the SSP585 pathways are highly implausible due to their assumption of a fivefold increase in the use of fossil fuels, essentially a worst-case scenario (Hausfather and Peters 2020). The obtained current climate data were based on WorldClim version 2.1, which was released in January 2020, and the Future climate scenarios were based on CMIP6, which was downscaled and calibrated with WorldClim v2.1 as baseline climate (Fick and Hijmans 2017).

Global climate models

An ensemble of twelve Global Circulation Models (GCMs), viz. CCESS-CM2, CMCC-ESM2, EC-Earth3-Veg, FIO-ESM-2-0, GISS-E2-1-G, HadGEM3-GC31-LL, INM-CM5-0, IPSLCM6A-LR, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL were considered for creation of an ensemble GCM. The average of each of the 19 bioclimatic variables was calculated from these 12 GCMs under the two future scenarios in two different time periods. The ensemble values were then used as predictive factors.

Multicollinearity test

Both Pearson's correlation coefficient and Variance Inflation Factor (VIF) were used to test for multicollinearity among the 19 bioclimatic variables. The threshold of the collinearity test for Pearson's correlation followed methods from Makori et al. (2017). We used the 'usdm' package in R software to carry out the multicollinearity test. The VIF function in this package was used to calculate the statistic, using the vifcor strategy. The vifcor strategy (Naimi and Araújo 2016) proposes a stepwise process for removing highly collinear variables. First, it identifies a pair of variables showing the maximum linear correlation (larger than the threshold) and removes the variable showing the higher VIF. This procedure is iterated until no pair of variables with a high correlation coefficient (above the threshold) exists. After the multicollinearity test, the remaining eight bioclimatic variables (Table 2) were used in predicting current and future distributions of the three IAPs.

Table 1. Characteristic features of the studied invasive alien plant species (Tiwari et al. 2005)

Scientific name (Family)	Common name (Local name)	First report in Nepal	Native range	Mode of reproduction	Total occurrence points (used in modelling)
<i>Ageratina adenophora</i> (Asteraceae)	Crofton weed (Kalo Banmara)	1952	Mexico	Seed/vegetative	263 (201)
<i>Chromolaena odorata</i> (Asteraceae)	Siam weed (Seto Banmara)	1825	Mexico, C and S America	Seed/vegetative	161 (117)
<i>Lantana camara</i> (Verbenaceae)	Lantana (Kirnekanda)	1848	C&S America	Seed/vegetative	98 (87)

Table 2. Bioclimatic predictor variables used for modelling

Predictor variables used	Code
Mean diurnal range (Mean of monthly (max temp-min temp))	BIO 2
Isothermality	BIO 3
Temperature seasonality	BIO 4
Temperature annual range (Max temperature of warmest month-min temperature of coldest month)	BIO 7
Mean temperature of driest quarter	BIO 9
Precipitation of driest month	BIO 14
Precipitation of driest quarter	BIO 17
Precipitation of warmest quarter	BIO 18

Data analysis

Species distribution modelling

Modelling was performed using the R environment version 4.3.2 (R Core Team 2023) with the biomod2 package (Thuiller et al. 2023). The ensemble model was created by using a suite of 10 algorithms, including three regression techniques (GAM: General Additive Model, GLM: General Linear Model, and MARS: Multivariate Adaptive Regression Splines), four machine-learning techniques (ANN: Artificial Neural Network, GBM: Generalized Boosting Model, RF: Random Forest, and XGBoost: Extreme Gradient Boosting training), two classification techniques (CTA: Classification Tree Analysis; FDA: Flexible Discriminant Analysis), and an envelope-style method similar to Bioclim (SRE: Surface Range Envelope). The use of the multi-model ensemble not only addresses variations among various GCMs but also produces outcomes that outperform those of individual models at a global and regional level (Aguirre-Gutiérrez et al. 2017).

The model development required background data, which included pseudo-absence. As actual absence data were unavailable, we followed the approach by Barbet-Massin et al. (2012), selecting at random 5,000 pseudo-absences located outside a 10 km buffer from the presence points. For model calibration, the study used 70% of the occurrence points (presence and pseudo-absence) as training data and tested the models with the remaining 30% as testing data, based on the methodology developed by Araújo et al. (2005). The study generated pseudo-absences three times and ran two evaluation runs per species, which resulted in 60 models per species (ten models, two

evaluation runs, and three pseudo-absence selection procedures) for each climate scenario.

Spatial analysis

To conduct the spatial analysis and predict the potential spread of the three IAPs across different physiographic and climatic zones and land use types, we first downloaded the most recent land use land cover map from 2019 from the International Centre for Integrated Mountain Development (ICIMOD) regional database (<https://rds.icimod.org/>). We then downloaded an elevation map with a 1x1 km resolution from the WorldClim website and downloaded the physiographic map from the Forest Research and Training Center. After acquiring all necessary data, we clipped the data to fit the study area. We then used ArcMap to determine potentially suitable areas of species habitat across physiographic zones, climatic zones, and land-use types.

Model validation and accuracy assessment

It is a common practice in Species distribution model studies to use the Area Under the Curve (AUC) scores for model selection; however, the use of AUC scores alone as the criterion for selecting a model can be misleading (Mainali et al. 2015). We used two validation metrics to evaluate the model validation and predictive performance: AUC of receiver operating characteristics and True Skill Statistics (TSS), to evaluate the models and to build an ensemble from the projection outputs of ten algorithms. AUC values range from 0 to 1, where values close to 0 represent inaccuracies, and AUC values ≥ 0.7 indicate high predictive skills (Mohammadi et al. 2019). TSS values fall between -1 and +1, such that values very close to +1 indicate almost perfect agreement of observations with model predictions, and TSS ≤ 0 indicates generally poor modelling performance (Somodi et al. 2017).

RESULTS AND DISCUSSION

Current and projected distribution under future climate scenarios

We mapped the distribution of the three IAPs in both present and projected future climate scenarios in Bagmati Province, Nepal. Under current climatic conditions, *A. adenophora* had the largest climatically suitable area with 4121.64 km², while *C. odorata* had the smallest, with 1964.07 km² (Table 3).

Table 3. Change in the climatically suitable habitat of the three invasive alien plants

Name of species	Current (km ²)	(2021-2040)				(2041-2060)			
		SSP245 (km ²)	Change (%)	SSP585 (km ²)	Change (%)	SSP245 (km ²)	Change (%)	SSP585 (km ²)	Change (%)
<i>Ageratina adenophora</i>	4121.64	4211.6	2.18	4390.22	6.52	4342.43	5.36	4409.8	6.99
<i>Chromolaena odorata</i>	1964.07	2137.14	8.81	2365.11	20.42	2271.1	15.63	2452.07	24.85
<i>Lantana camara</i>	2140.34	2407.41	12.48	2937	37.22	2431.7	13.61	3012.2	40.73

Climate change will increase the area of suitable habitat for all three IAPs. Under the SSP245 future change scenario, for the time period 2021-2040, the area of suitable habitat for *A. adenophora*, *C. odorata*, and *L. camara* increases by 2.18%, 8.81%, and 12.48%, respectively, compared to the current climate. Under the same climate change scenario for the time period 2041-2060, the area of suitable habitat for *A. adenophora*, *C. odorata*, and *L. camara* increases by 5.36%, 15.63%, and 13.61%, respectively, compared to the current climate (Figure 2).

In the context of the SSP585 climate change scenario for the period 2021-2040, the area of suitable habitat for *A. adenophora*, *C. odorata*, and *L. camara* increases by 6.52%, 20.42%, and 37.22%, respectively, compared to the current climate. Under the same climate change scenario for the period 2041-2060, the area of suitable habitat for *A. adenophora*, *C. odorata*, and *L. camara* increases by 6.99%, 24.85%, and 40.73%, respectively, compared to the current climate (Figure 3).

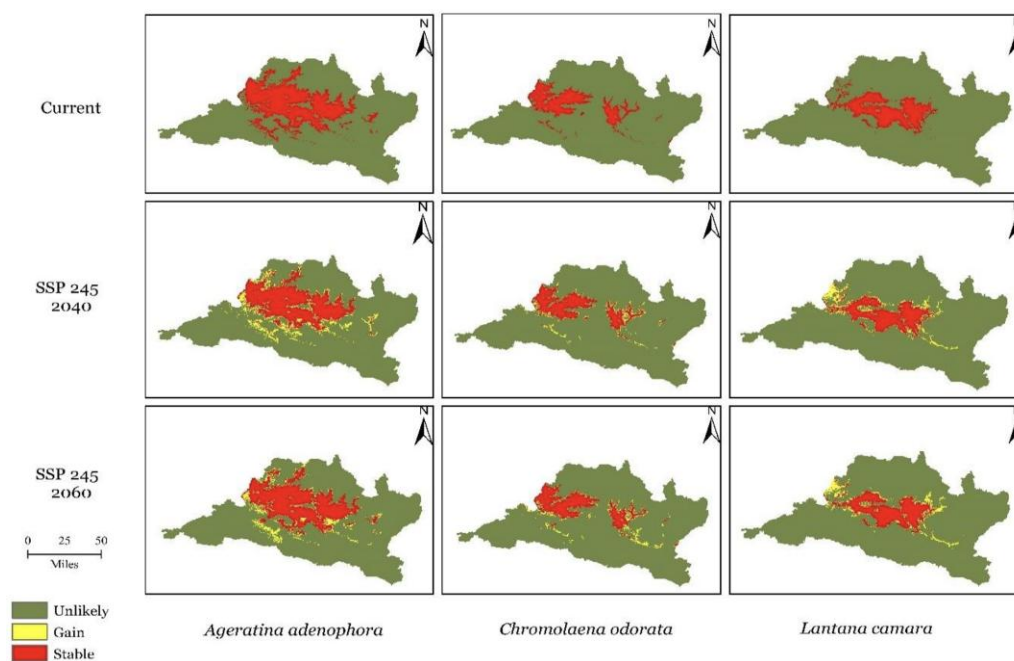


Figure 2. Changes in the suitable habitat for three IAPs in Bagmati province, Nepal, with future climate scenarios SSP245 for the period 2021-2040 and 2041-2060

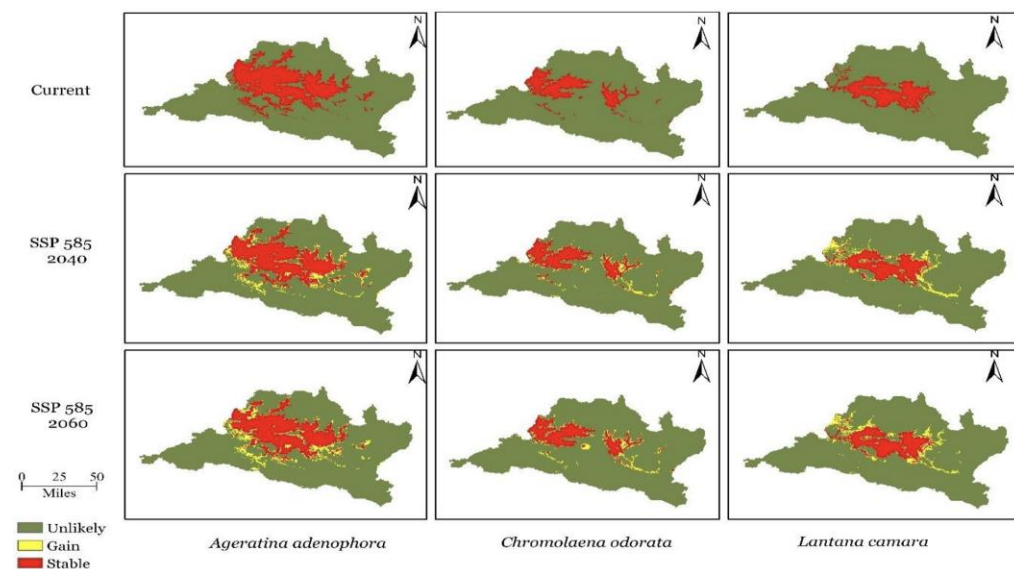


Figure 3. Changes in suitable habitat for three IAPs in Bagmati province, Nepal, with future climate scenarios SSP585 for the period 2021-2040 and 2041-2060

The predicted suitable habitat for the three IAPs was also analyzed across physiographic zones, climatic zones, and land use types. We found notable differences in habitat suitability for the three IAPs across the various physiographic zones, climatic zones, and land use categories in Bagmati Province.

Current and projected distribution based on physiography

The projected areas favorable for IAPs in both current and future climate scenarios (SSP245 and SSP585) were mainly in the Middle Mountain zone among the four physiographic zones of Bagmati Province (Siwalik, Middle Mountain, High Mountain and High Himal) (Figure 4). *A. adenophora* accounts for 84.71% of its suitable habitat in Middle Mountain, *C. odorata* for 96.80% and *L. camara* for 99.67% under the current climate scenario. A similar

trend is seen in both future climate scenarios (SSP245 and SSP585 for the time period, 2021-2040 and 2041-2060), with the vast majority of each species' suitable area remaining concentrated in Middle Mountain.

Current and projected distribution based on climatic zones

The tropical zone (located below 1,000 m altitude) was found to have a more suitable habitat for *C. odorata* than for the other two IAPs (Figure 5). The sub-tropical zone (1,000 and 2,000 m elevation) was highly suitable for *A. adenophora* and *L. camara*. The temperate zone (2,000 to 3,000 m) currently has no suitable habitat for *L. camara* and *C. odorata*. These patterns persist under future climate scenarios, with *C. odorata* remaining largely restricted to the tropical lowlands and *L. camara* and *A. adenophora* largely in the sub-tropics, and very limited expansion of any species into the temperate zone.

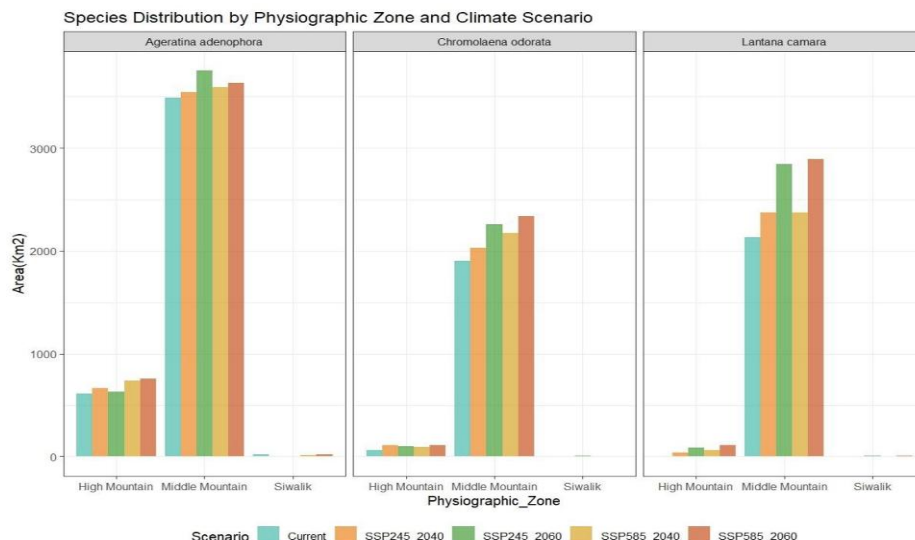


Figure 4. Area of suitable habitat for three IAPs based on physiography under the current climate scenario and future climate scenarios SSP245 and SSP585

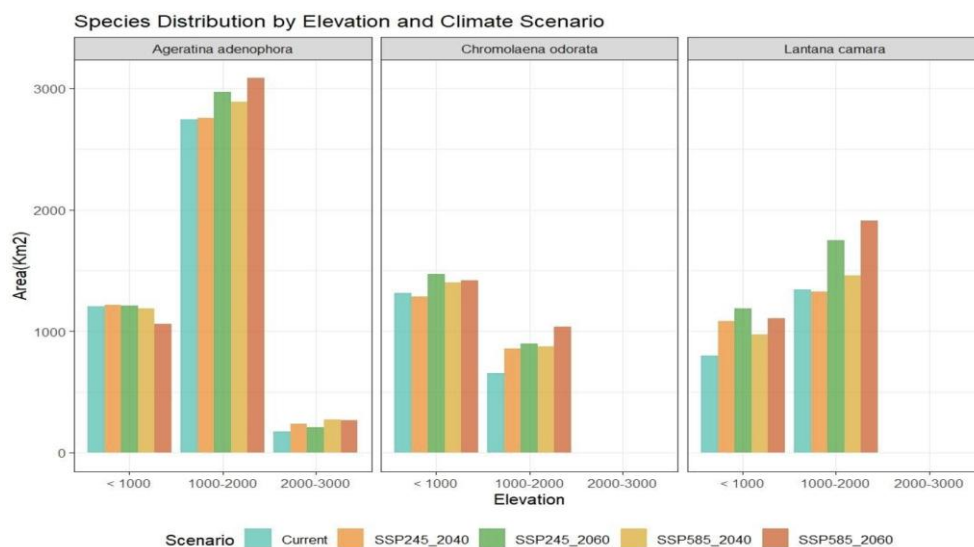


Figure 5. Area of suitable habitat for three IAPs based on climatic zones under the current climate scenario and future climate scenarios SSP245 and SSP585

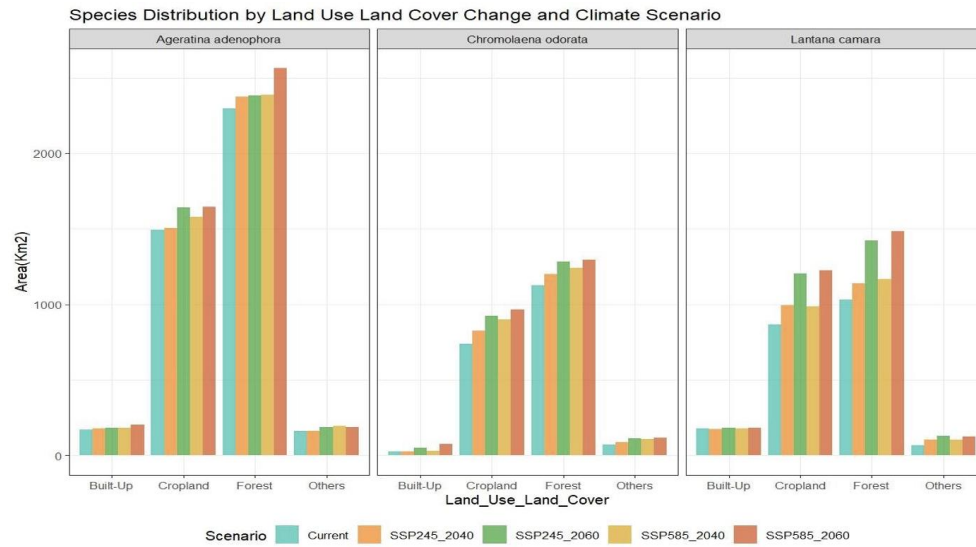


Figure 6. Area of suitable habitat for three IAPs based on land use under the current climate scenario and future climate scenarios SSP245 and SSP585.

Current and projected distribution based on land use

Under the current climate, forests, croplands, and built-up areas are all suitable for all three IAPs (Figure 6). The model predicts that the suitable areas of all three species will increase in forested areas under both SSPs. The largest forest-area increase is projected for *C. odorata*, with a 14.93% increase during 2041-2060 under SSP585, and the smallest forest increase for *A. adenophora* (3.85% for 2041-2060 under SSP245).

The suitable area of cropland is projected to increase for all three species under both SSPs. The largest cropland increase is projected for *L. camara*, at 41.28% by 2060 under SSP585, and the smallest for *A. adenophora*, at 10.13% by 2060 under SSP585. The suitable area of built-up land is projected to increase for *A. adenophora* under both SSPs. However, suitable habitat for *C. odorata* and *L. camara* is projected to decrease in built-up areas under SSP245 for 2021-2040, by 5.56% and 0.88%, respectively. By contrast, the largest increase in built-up areas is projected for *L. camara*, with a 175.00% increase by 2060 under SSP585 (noting that *L. camara*'s current area in built-up land is small, so relative increases appear large). All other remaining land types, such as riverbeds, grasslands, and other wooded areas, are expected to become more suitable for all three IAPs under both climate scenarios (Figure 6).

Model performance and variable importance

The performance of models using TSS and AUC statistics is shown in Table 4. The AUC for the models used ranged from 0.85 to 0.92, and True Skill Statistics (TSS) values ranged from 0.51 to 0.67. As shown in the table, *C. odorata* has better model performance under both future climate scenarios than under the current climate, as indicated by the higher values for both metrics (TSS and AUC). For instance, *C. odorata* has a TSS of 0.60 in the current climate, which increases to 0.67 and 0.65 under

SSP245 and SSP585, respectively, for time period 2021-2040, indicating better performance of the model.

Among the eight predictor variables used in the model, precipitation of the driest month (BIO 14) is the most significant variable, with an importance of 46% for the current climate. For the period 2021-2040, under SSP245, the mean diurnal range (BIO 2) is the most significant, with an importance of 42%, while under SSP585, the mean temperature of the driest quarter (BIO 9) is the most significant, with an importance of 45%. For the period 2041-2060, the mean diurnal range (BIO 2) remains the most significant variable under SSP245 (42%) and is also most significant under SSP585 (46%). Table 5 displays the importance value of each variable.

Table 4. Performance of the models on TSS and AUC evaluation statistics under current and future climate. Performance is calculated on the average of 60 different model runs

Name of species	Climate scenarios	Evaluator	
		TSS	AUC
<i>Ageratina adenophora</i>	Current	0.56	0.87
	SSP245 (2021-2040)	0.58	0.86
	SSP245 (2041-2060)	0.56	0.86
	SSP585 (2021-2040)	0.54	0.85
	SSP585 (2041-2060)	0.57	0.87
<i>Chromolaena odorata</i>	Current	0.60	0.89
	SSP245 (2021-2040)	0.67	0.92
	SSP245 (2041-2060)	0.66	0.90
	SSP585 (2021-2040)	0.65	0.91
	SSP585 (2041-2060)	0.64	0.90
<i>Lantana camara</i>	Current	0.59	0.90
	SSP245 (2021-2040)	0.54	0.87
	SSP245 (2041-2060)	0.51	0.87
	SSP585 (2021-2040)	0.56	0.89
	SSP585 (2041-2060)	0.53	0.88

Table 5. Most significant predictor variables for the studied Invasive species and their relative importance

Time Period		Most significant variable	Code	Variable importance value (%)
Present		Precipitation of driest month	BIO 14	46
2021-2040	SSP245	Mean diurnal range (Mean of monthly (max temp-min temp))	BIO 2	42
	SSP585	Mean temperature of driest quarter	BIO 9	45
2041-2060	SSP245	Mean diurnal range (Mean of monthly (max temp-min temp))	BIO 2	42
	SSP585	Mean diurnal range (Mean of monthly (max temp-min temp))	BIO 2	46

Discussion

We modelled the distribution of three IAPs (*A. adenophora*, *C. odorata*, and *L. camara*) in Bagmati Province, Nepal, under current and future climate scenarios. The AUC and TSS values obtained in this study fall within the acceptable range and can be considered robust. We therefore consider our model performance to be good enough for interpreting the overall results for these three IAPs. This study finds that the habitats of these three IAPs are increasing under both SSP245 and SSP585 future climate scenarios. These results are consistent with a study by Lamsal et al. (2018) in the Himalayan region, including Nepal, which found that the habitats of *A. adenophora*, *C. odorata*, and *L. camara* increased overall under RCP 4.5 and RCP 8.5 compared with the current climate.

This study thus adds to existing knowledge of the role of climate change as one of the important drivers for the expansion of invasive species in Nepal (Shrestha et al. 2018; Thapa et al. 2018; Shrestha and Shrestha 2019) and around the globe (Bellard et al. 2018; Finch et al. 2021; Turbelin and Catford 2021). The projections show an increase in suitable habitat for the studied species. There is a high chance that the 20-year Globally averaged Surface Air Temperature (GSAT) from 2021 to 2040 will be 1.5°C higher than the average from 1850 to 1900 in scenario SSP585 (Lee et al. 2021), which also projects for scenario SSP245. Annual global land precipitation will likely increase over the 21st century as GSAT rises. For globally averaged annual land precipitation, the projected change range over 2081-2100, relative to 1995-2014, is 0.9-12.9% under the high emissions SSP585 and 1.5-8.3% under SSP245 (Lee et al. 2021). These trends suggest that climatic suitability for IAPs will increase alongside future increases in temperature and precipitation in tropical, sub-tropical, and temperate climatic zones of Bagmati Province.

Mean diurnal range (Bio2), representing the average difference between daily maximum and minimum temperatures, suggests that regular temperature fluctuations may contribute to the spread of IAPs. In a separate study in the Western Himalaya region, BIO 2, together with the minimum temperature of the coldest month and mean temperature of the driest quarter, significantly affected the distribution of 11 IAP species (Thapa et al. 2018). BIO 2 has also been found to be an important variable in predicting possible habitats of invasive species such as *Oxalis debilis* in China (Qin and Li 2023). The mean temperature of driest quarter (BIO 9) also shows a strong effect on the proliferation of these species, suggesting that

such environmental factors may affect their distribution patterns.

The effectiveness of relative variable importance in SDMs depends on the spatial autocorrelation structure of the predictors, the type of species response to the environmental gradients, and the choice of modelling algorithms and climate data (Harisena 2019; et al. 2021; Rodríguez-Rey and Jiménez-Valverde 2024). However, accuracy in SDMs can also be compromised by the scale at which environmental data are sampled and by the spatial resolution of the climate variables used in modelling. Those factors should be taken into consideration when interpreting results from the species distribution models to make sure that the results are reliable and applicable in conservation efforts.

Climatic suitability and distribution patterns based on physiography and climatic zones

Under both current climatic conditions and future climate scenarios (SSP245 and SSP585), the Middle Mountain zone has more climatically suitable areas for all three IAPs compared with other physiographic regions in Bagmati Province. This finding is consistent with the result obtained in a recent study by Shrestha and Shrestha (2019), used modelling techniques to evaluate the distribution of 24 IAP species across Nepal. They found that the Middle Mountain region was the most prone to invasion, hosting the largest invasion hotspots with the greatest number of species. Moreover, a study by Poudel et al. (2020) using Maxent to investigate the distribution of *A. adenophora* in the Chitwan Annapurna Landscape of Nepal found a higher degree of climatic suitability for this species in the Middle Mountain region, corroborating our results.

The elevation of the Middle Mountain region ranges between 1,000 and 2,500 m above sea level (DHM 2017) and has been identified as having high biodiversity and species richness compared to other regions (Bhattacharjee et al. 2017). It also contains a large number of community-managed forests, which have been core to conservation and livelihood campaigns in Nepal (CFSC 2023). These corroborating findings underline the susceptibility of the Middle Mountain region to invasive plant encroachment, suggesting a need for targeted management interventions in these areas.

The study shows that *C. odorata* had its largest area of suitable habitat within the tropical zone of Bagmati Province, while the sub-tropical zone between 1,000 and 2,000 m above sea level has the largest areas suitable for *A. adenophora* and *L. camara*. These findings are in line with

those of a recent study by Shrestha et al. (2018), which concluded that most IAPs primarily occupy tropical and sub-tropical areas ranging in elevation from 100 to 2,100 m, notwithstanding some methodological and data differences. Similarly, Panday et al. (2021) affirm that *C. odorata* is the most dominant IAP species in Parsa National Park, located in central Nepal, belonging to the tropical climatic zone. Adhikari et al. (2023) stated in the study that *C. odorata* is primarily found in humid tropical, subtropical, and warm temperate climates as seen from global perspectives. For *L. camara*, Lamsal et al. (2018) predicted an increase in habitat suitability towards southern parts of northern India and the borders of Nepal and Assam, which include altitudes from 500 to 1,300 m above sea level, consistent with our findings. Lamsal et al. (2018) projected that many of the IAPs studied will continue to shift southwards, especially in the central and eastern foothills of the Himalayas. Negi et al. (2019) pointed out that *L. camara* flourishes over a wide range of habitats from sea level to 1,800 m above sea level and tolerates annual rainfall between 750 mm and 5000 mm. This study found limited suitable habitat for *L. camara* and *C. odorata* in temperate zones in both the current and future projected climate scenarios. In contrast, *A. adenophora* has suitability under the temperate climatic zones of this province, and there is evidence that it is shifting upwards and colonizing new areas with the recent changes in climate noticed in Langtang National Park (Lamsal et al. 2017).

In addition, this species possesses phenotypic plasticity, which allows it to occupy a broad climatic niche (Zhao et al. 2013). None of the three IAPs has a suitable habitat in the sub-alpine and alpine climatic zones. Factors such as low propagule pressure, the lack of species pre-adapted to harsher conditions, limited anthropogenic disturbance, and the lower invisibility of natural high-elevation communities likely explain the reduced occurrence of invasive species within alpine ecosystems (Alexander et al. 2016). The results of this study are in harmony with previous studies by Lamsal et al. (2018) and Thapa et al. (2018), although the distribution trend of invasive species was found to decline with an increase in elevation, while considering the variation in methodologies and data in Southeast Asia's Himalayan region. Likewise, Shrestha et al. (2018) and Shrestha and Shrestha (2019) found that invasion rates are slower in highlands in Nepal due to adverse climate conditions under future climate change scenarios. McDougall et al. (2011) emphasized the comparatively lower invasion risk in mountain ecosystems compared to other ecosystems. The three IAPs under investigation in this study originated from tropical regions (Tiwari et al. 2005) and show different growth forms and physiological and morphological characteristics than plants from high elevations.

Therefore, large-scale northward and upward expansion as a result of a warming climate in the future is not expected in this context, in contrast to findings for cold-adapted plant species by other studies (Lamsal et al. 2017, et al. 2018; Shrestha and Shrestha 2019). However, lower invasion rates of high-elevation mountain ecosystems compared with lowland ecosystems could change as a

result of globalization and climate change, increasing the potential threat that invasive plants will present to high-elevation biodiversity (González-Trujillo et al. 2024). It is, therefore, important to consider regional climate variability when looking toward the potential impacts of invasive species. Accordingly, proactive measures are needed to control the spread of invasive plant species, especially in areas that are more vulnerable as a result of warming climate trends.

Climatic suitability of IAPs across various land uses

The area of suitable habitat for the three IAPs is predicted to increase in all land use types (forests, agricultural lands, riverbeds, grasslands, and other wooded areas) under both SSP245 and SSP585 in the 2021-2040 and 2041-2060 periods. This finding is consistent with recent studies, from Shrestha and Shrestha (2019), Saranya et al. (2021) and Sharma et al. (2022), which highlight the fact that the highest density of suitable habitats for IAPs is located in agricultural lands and areas with forest cover. This confirms that these IAPs prefer to invade agricultural lands and open forests.

This high suitability of agricultural and forest lands for IAPs is a big threat to local economies and livelihoods (Shrestha and Shrestha 2019), especially in countries like Nepal, where agriculture and forestry are primary sources of livelihood for most local communities. The invasive flora can cause severe impacts on agricultural lands and has the potential to significantly affect agricultural productivity and biodiversity (Early et al. 2016; Paini et al. 2016). Moreover, the existence of these alien species in proximity to forests disturbs the reproduction and spread of native species (Hiremath et al. 2018). Local communities, whose livelihoods and employment opportunities heavily depend on farming and forests, have already been affected by IAPs through increased labor required for weeding, reduced crop production, livestock poisoning, diminished forage supply, and negative impacts on forests (Shrestha et al. 2019).

This study predicts a tremendous expansion in the dissemination of *L. camara* along riverbeds (105.88%), other wooded lands (100%) and grasslands (83.33%) compared to forest (37.99%) and croplands (39.02%) under future climate scenarios SSP585 for the periods 2021-2040 and 2040-2061. This result is consistent with the findings of Negi et al. (2019) that *L. camara* can grow in diversified ecosystems. Ramaswami and Sukumar (2013) had predicted that *L. camara* prefers forest edges and gaps, which hinted at its ability to thrive in specific environments. Although *L. camara* generally does not invade intact forests, it easily colonizes disturbed sites where natural forests have been disrupted, especially by activities such as logging, which create gaps (Negi et al. 2019). Moreover, an increased human activity-related scenario, characterized by deforestation and clearance for agricultural lands, is likely to increase the forest edges and gaps, ultimately facilitating the invasion of *L. camara* in such disturbed areas.

Moreover, our research also underlines the highest infestation of *A. adenophora* in riverbeds (38.89% increase in suitable area) for both scenarios (SSP245 and SSP585)

during 2041-2060, in comparison to other classes of land use. This predicted suitability along the riverbeds is in line with a study conducted in China, which mentioned that the habitat of *A. adenophora* is potentially suitable along waterbodies (Xian et al. 2022). These river networks serve as corridors for the rapid spread of *A. adenophora* (Horvitz et al. 2014), which makes it more likely that riverbeds may provide suitable conditions for its rapid growth and spread, with possible large ecological and environmental impacts. Consistent with this, our study indicated that *C. odorata* had a high proliferation rate of 88.89% in riverbeds and 175% in built-up areas under climate scenario SSP585 during the time period 2041-2060, indicating its high adaptability to aquatic and urban ecosystems. This would require tight monitoring and control over the spreading of this species in these areas to avoid likely ecological disturbances and damage to biodiversity. It must be pointed out that *C. odorata* is shade-intolerant; therefore, it does not invade intact forest areas (Sharma et al. 2022). The actual distribution of the plant invaders will hinge on many more factors besides climate change: dispersal mechanisms, land-use practices, and control efforts. In this study, they fall outside the margin.

While our study provides important insights to the distribution of the three IAPs in Bagmati Province, Nepal, under current and future climate conditions, it is worth noting that an additional 24 IAPs have been modelled and mapped across Nepal by Shrestha and Shrestha (2021), whose current distribution within Bagmati Province remains largely unknown. In addition, the real distribution of the three selected IAPs is still uncertain. The results obtained are only predictions based on species distribution models under two climate change scenarios, SSP245 and SSP585. The modelling process has several limitations, including the selection of GCMs (Steen et al. 2017), model complexity (Wright et al. 2015), threshold values used to generate binary maps (Liu et al. 2017), among others. These factors might influence the results of models, and consequently, the outputs.

In conclusion, this study offers essential insights into how climate change affects the distribution of IAPs in Bagmati Province, Nepal, revealing significant shifts in habitat suitability across various climate scenarios. Currently, *A. adenophora* occupies the largest climatically suitable area, while *C. odorata* has the smallest. However, future projections indicate a dramatic expansion in suitable habitats for all three IAPs. Under the SSP245 and SSP585 scenarios, *L. camara* is expected to experience the most substantial growth, with habitat increases potentially exceeding 40% by 2060 under SSP585, highlighting the severe threat posed by climate change. The improved accuracy of predictive models under future climate scenarios suggests that forecasts of *C. odorata*'s distribution will become more reliable as climate conditions evolve. This enhancement is vital for devising effective management and control strategies, especially in areas identified as highly vulnerable. Notably, the Middle Mountain physiographic zone emerges as a critical hotspot for the proliferation of IAPs, with a significant concentration of suitable habitats for *A. adenophora*, *C.*

odorata, and *L. camara*. The tropical zone below 1,000 m is particularly favorable for *C. odorata*, while the subtropical zone between 1,000 and 2,000 m is highly suitable for *A. adenophora* and *L. camara*. Key land types such as forests, croplands, and built-up areas are projected to experience notable expansions in IAP habitat suitability, for instance, *C. odorata* showing a 14.93% increase in forested areas and *L. camara* seeing substantial rises in cropland (41.28%) and built-up areas (175%) by 2060 under SSP585. These findings underscore the dynamic nature of Species Distribution Modelling, highlighting the need for ongoing adjustments to predictive models to account for evolving climate variables. Effective management strategies must be agile and adaptive to these changes to mitigate the growing threat from IAPs.

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