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Assessing Potential Distribution Zone Prone to Invasion Risk of *Hyptis suaveolens* (L) in Jharkhand, Eastern India Using MaxEnt

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ABSTRACT

The rapid spread of alien invasive plant species has emerged as one of the serious issues for forest composition, biodiversity, and ecosystem services. The most probable distribution range of *Hyptis suaveolens* was modeled for Jharkhand using MaxEnt for the years 2020 and 2050 under different Representative Concentration Pathways (RCPs) *i.e.* 2.6, 4.5, 6.0, and 8.5. The model predicted that at present ~9.09 % of the geographical area of Jharkhand is under High-Risk Zone (HRZ) to the infestation of *H. suaveolens* and by 2050 the potential area of invasion may increase to ~10.48 - 11.32%. The model predicted a prominent distribution of *H. suaveolens* in agro-climatic sub-zone IV with ~ 5.51 % of sub-zone area under HRZ, followed by~3.44% for sub-zone VI. The study predicted dominance of the distribution of *H. suaveolens* in sub-zone IV to continue in the future and the potentially infested area may increase to ~ 5.93-6.29% and ~3.95-4.88% for sub-zone IV and VI respectively. In contrast, a very small ~0.14% area was found suitable for potential distribution range of *H. suaveolens* in sub-zone V and in future depending upon RCP, the potentially infested area may remain same or even decrease slightly across most RCPs barring 6.0, where the area may increase to ~0.26%. The study showed tropical dry deciduous forests and non-forest classes are at greater risk of infestation of *H. suaveolens*. Bio_2 (mean diurnal range) and Bio_1 (annual mean temperature) contributed most in limiting the distribution of *H. suaveolens* for the years 2020 and 2050 respectively. The study provides prior identification of the potential distribution sites prone to infestation of *H. suaveolens*, enabling prioritization of treatment areas to control further invasion.

Key words: Climate change, *Hyptis suaveolens*, High-Risk Zone, Invasive species, RCP

INTRODUCTION

Invasive species negatively impact the forests, ecosystems, and native species and harm human health through continuous spread (Année 2009). It may have harmful impacts on hydrological resources, carbon depletion, and nutrient cycles, including phosphorus and nitrogen (Polley et al. 1997). After habitat fragmentation, plant intrusion is considered the most severe threat to the ecosystem and biodiversity (Madren 2011). Globalization, transportation, establishment, and landscape spread are major factors for a rapid increase in the invasion of alien species (Rai 2015). Further, the global warming effect has also led to species migration (Masters and Norgrove 2010), leading to an altered and compromised ecosystem (Burgiel and Muir 2010), competition for space and nutrition (Borokini 2011) and affecting the equality of species in the community (Sharma et al. 2009).

Hyptis suaveolens (L), locally known as Vilayati tulsi, bush mint or bush tea (Mishra et al. 2021a), is slightly woody or shrubby at the base and belongs to the Lamiaceae family. *H. suaveolens (L),* which is native to the tropical region of Mexico, and apart from *Lantana camara,* is considered a major threat to Indian deciduous forest (Sharma et al. 2005). Due to its rugged nature, it causes many germination problems by releasing allelo-chemicals (Islam and Kato-Noguchi 2013) and endangered the existence of native species and livestock farming (Murthy et al. 2007), and restricts the native growth in floodplains, disturbed patches and riparian vegetation (Queensland Government 2012). However, it has some pharmacological significance, such as anti-Cancer (Mudgal et al. 1997), aromatic, anti-inflammatory (Mishra et al. 2021a), and insecticide (Adda et al. 2011).

The distribution of *H. suaveolens* mostly occur along agricultural land, in the vicinity of forests, open forest areas, grazing sites, disturbed areas, beside rail tracks, roadsides, and abandoned urban sites (Gayatri et al. 2021, Verma and Mishra 1992), riverbanks, wet margins of ponds, etc. (Islam et al. 2014). Generally, the distribution of *H. suaveolens* is observed in sub-tropical and semi-arid environments; however, it can also be present around human settlements (Schwarzkopf et al. 2009). In India, well-established *H. suaveolens* colonies are distributed in the northeast region, the Vindhyan hills, the Deccan plateau, and Andaman and Nicobar (Yoganarasimhan 2000).

The early identification of potential areas prone to invasions is crucial, and modeling potential risk sites can play a vital role in mitigating the invasion threat (Lui 2011). Many researchers have utilized an alternate model to predict reasonableness using the Species Distribution Model (Bradley et al. 2010) to evaluate the species distribution. Many studies have been performed globally using different SDM tools mainly Generalized Linear Model (GLM) and Generalized Additive Model (GAM) (Guisan et al. 2006), General Rule Set Production (GARP) (Elith et al. 2006, Stockwell D. 1999), Maximum entropy (MaxEnt) (Phillips et al. 2006), bioclimatic envelope (BioClim) and DOMAIN (Elith et al. 2006). MaxEnt is the most widely used modeling tool, provides a high degree of accuracy, and has various additional modeling features (Graham et al. 2004).

Over the years, considerable work on invasive species focused mainly on *L. camara* (Paul et al. 2021, Qin et al. 2016; Chaudhary et al. 2021). However, relatively little information is available on other prominently distributed invasive species, which may cause severe harm to biodiversity and ecosystem services. In Jharkhand, significant rapid growth, high density, and abundance of some major invasive species, including *L. camara*, *Chromolaena odorata*, and *H. suaveolens,* have a perceived harmful impact on indigenous species (Lal et al. 2012). The present study set out to study the current potential distribution range of *H. suaveolens,* and response to climate change by 2050under different representative concentration pathways (RCP) scenarios, *i.e.*, RCP 2.6, 4.5, 6.0, and 8.5 in Jharkhand. The outcome of the study shall provide significant insight on present distribution status and identification of potential sites prone to future infestation of *H. suaveolens* in the region, enable early detection of potential invasion sites, and plan management strategies to control future expansion.

MATERIALS AND METHODS

Study area

Jharkhand has a repository of various forest species located in the eastern part of India (Fig.1), comprising 23,506 km^2 of forest area, which is ~ 29.62% of the state's total geographical area (FSI 2019). Physiographically, the state has four significant plateaus isolated by the Chotanagpur plateau, the most prominent part of Jharkhand. According to the Indian State of Forest Report (ISFR)-2019, the state falls under Moist Deciduous and Dry Deciduous Forests. Agro-climatically, the state is divided into three sub-zones viz., sub-zoneIV, sub-zone V, and sub-zone VI characterized by humid, tropical, and subtropical climate (Mishra et al. 2021b).

Collection of species occurrence data

An ecological survey was carried out in the state of Jharkhand for recording occurrence data of *H. suaveolens,* and sample data for its occurrence were collected from 100 well-distributed sample plots (32m x 32 m) across different parts of Jharkhand encompassing all the three agro-climatic sub-zones. The geographical coordinates of species occurrences were recorded using a GPS device (Garmin etrex 30) at an accuracy level of ≤10 meters.

Environmental variables

We used 19 bioclimatic variables (Fick and Hijmans 2017) having a cell size of 30 arc seconds, acquired from Worldclim website (www.worldclim.org), elevation, hillshade, aspect, slope, layers derived from Shuttle Radar Topography Mission (SRTM) DEM data set (Mishra et al. 2019) acquired from earth explorer (https://earthexplorer.usgs.gov), soil layer from the FAO portal (http://www.fao.org), human influence data acquired from SEDAC website (http://sedac.ciesin.columbia.edu/data/set/wildareas-v2-human-influence-index-geographic/data-download) and a land use/ land cover (LULC) map derived from Landsat 8 operational land imager

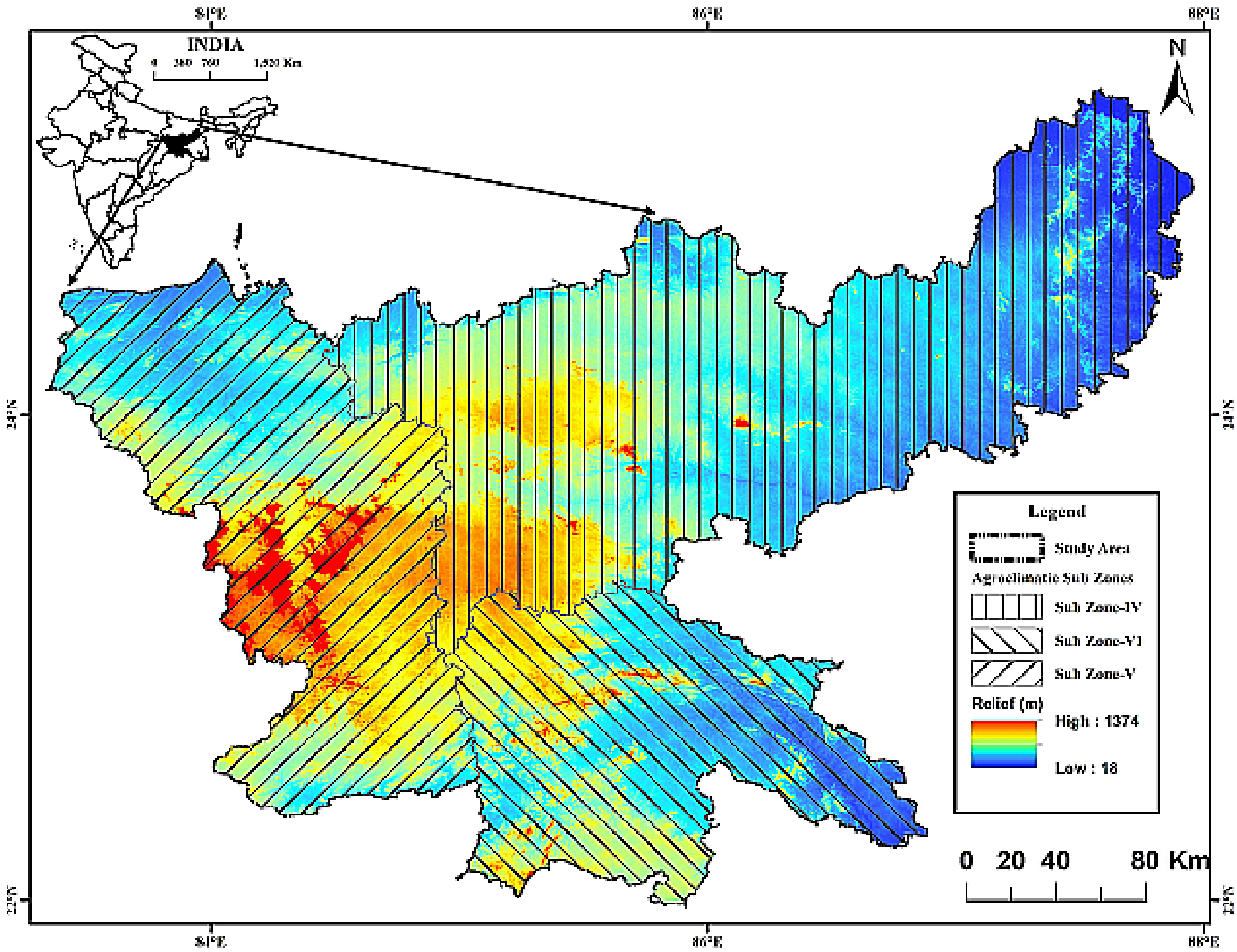

Figure 1. Location map of the Jharkhand state depicting the agro-climatic sub-zones with relief distribution.

(OLI) datasets for November 2018 acquired from earth explorer data portal. The LULC map was prepared using Spectral Angle Mapping (SAM) supervised classification techniques in QGIS software (Congedo, 2021) with 82 % overall accuracy and 0.82 kappa coefficient. For 2050, we employed IPSL-CM5A-LR, Global Climate Model (GCM), termed as earth system model (Dufresne et al. 2013) acquired from Climate Change Agriculture and Food Security (CCAFS) (www.ccafs-climate.org). The policy-relevant and latest (van Vuuren et al. 2011) Delta method IPCC AR5 CMIP5 statistical downscaled RCP datasets for RCP 2.6, 4.5, 6.0, and 8.5 were employed in the present study. These datasets are used in more than 350 numbers of ecosystems and agricultural sciences-related studies (Navarro-Racines et al. 2020).

Multicollinearity test

Choose the bioclimatic layers based on a multicollinearity test to reduce model overfitting (Jueterbock et al. 2016). We developed a R programming script using R studio to find out the unique layers (that have not overfitted) Pearson coefficient value (±0.7) (Chaudhary et al. 2021, Aguirre-Gutiérrez et al. 2013) (Table 1). We choose 14 individual environmental layers for the current scenario, including eight bioclimatic layers and slope, aspect, hillshade, LULC, soil, and human influence. For the future climatic scenario (2050), we used only 19 bioclimatic variables, and other variables due to the dynamic and changeable nature over time as the cause of the expansion of built-up land and other anthropogenic factors were not considered (Emiru et al. 2018).

Table 1. Multicollinearity test (±r) table for exclude overfitted variables. Pearson Correlation Coefficient Value = ± 0.7 (Chaudhary et al. 2021, Aguirre-Gutiérrez et al. 2013) Selected Variables are Aspect + Bio_02 + Bio_06 + Bio_08 + Bio_09 + Bio_12 + Bio_14 + Bio_17 + Bio_18 + Hillshade (HS) + LULC + Slope + Soil + Human Influence (HI) (14 variables)

Layers	AL	AS	Bio_0	Bio_02	Bio_03	Bio_04	Bio_05	Bio_06	Bio_07	Bio_08	Bio_09	Bio_10	Bio_11	Bio_12	Bio_13	Bio_14	Bio_15	Bio_16	Bio_17	Bio_18	Bio_19	HS	LULC	Slope	Soil	HI
AL	**1**																									
AS	0.05	**1**																								
Bio_01	**-0.9**	-0.06	**1**																							
Bio_02	0.23	0.07	-0.21	**1**																						
Bio_03	-0.37	-0.04	0.26	-0.54	**1**																					
Bio_04	0.08	0.07	-0.16	0.69	**-0.81**	**1**																				
Bio_05	-0.14	0	0.39	0.62	-0.62	0.56	**1**																			
Bio_06	-0.62	-0.09	**0.83**	-0.55	0.4	-0.54	0.17	**1**																		
Bio_07	0.32	0.07	-0.26	**0.91**	**-0.81**	**0.86**	**0.71**	-0.56	**1**																	
Bio_08	**-0.98**	-0.03	**0.88**	-0.18	0.26	0.02	0.21	0.58	-0.23	**1**																
Bio_09	-0.41	0	0.42	0.25	-0.31	0.45	0.51	0.14	0.32	0.45	**1**															
Bio_10	-0.6	-0.03	**0.82**	0.21	-0.26	0.28	**0.83**	0.59	0.27	**0.75**	0.58	**1**														
Bio_11	**-0.7**	-0.08	**0.89**	-0.37	0.46	-0.52	0.24	**0.95**	-0.47	0.65	0.18	0.64	**1**													
Bio_12	0.18	-0.03	-0.13	-0.09	0.57	-0.68	-0.33	0.09	-0.34	-0.29	-0.42	-0.36	0.2	**1**												
Bio_13	0.32	0.02	-0.26	0.36	0.17	-0.24	0.01	-0.19	0.15	-0.39	-0.23	-0.23	-0.04	**0.82**	**1**											
Bio_14	0.59	0.04	-0.47	0.49	-0.44	0.33	0.29	-0.42	0.54	-0.55	-0.07	-0.11	-0.44	0.09	0.32	**1**										
Bio_15	0.18	0.08	-0.12	**0.77**	**-0.75**	**0.79**	**0.7**	-0.4	**0.88**	-0.11	0.4	0.35	-0.33	-0.35	0.2	0.38	**1**									
Bio_16	0.33	0	-0.22	0.29	0.2	-0.33	0.01	-0.09	0.08	-0.41	-0.26	-0.2	0.03	**0.87**	**0.96**	0.32	0.11	**1**								
Bio_17	0.38	0.05	-0.47	0.35	-0.1	0.19	-0.11	-0.54	0.29	-0.37	-0.15	-0.36	-0.48	0.24	0.32	0.6	0.05	0.29	**1**							
Bio_18	-0.17	-0.03	0.05	-0.44	**0.78**	**-0.72**	-0.62	0.21	-0.67	0.08	-0.38	-0.39	0.27	0.63	0.29	-0.3	-0.64	0.31	-0.03	**1**						
Bio_19	0.61	0.04	-0.6	0.49	-0.42	0.38	0.11	-0.61	0.53	-0.57	-0.08	-0.28	-0.6	0.05	0.24	**0.71**	0.27	0.23	**0.76**	-0.29	**1**					
HS	-0.03	0.28	0.01	0.04	-0.05	0.08	0.04	-0.02	0.05	0.04	0.04	0.04	-0.02	-0.07	-0.04	0	0.05	-0.05	0.03	-0.05	0.02	**1**				
LULC	-0.38	-0.02	0.34	-0.13	0.12	-0.01	0.05	0.26	-0.14	0.37	0.17	0.24	0.26	-0.12	-0.2	-0.13	-0.16	-0.21	-0.09	0	-0.12	0.07	**1**			
Slope	0.27	0	-0.26	0.04	0	-0.06	-0.13	-0.18	0.02	-0.27	-0.12	-0.24	-0.18	0.15	0.16	0	0.05	0.19	0	0.05	0.06	-0.09	-0.45	**1**		
Soil	0.01	-0.02	-0.02	0.03	-0.04	0.06	-0.01	-0.08	0.04	-0.02	0.01	0	-0.06	-0.08	-0.16	-0.07	-0.11	-0.1	0.13	-0.15	0.06	0	0.19	-0.11	**1**	
HI	-0.32	-0.05	0.3	-0.2	0.17	-0.1	0	0.28	-0.21	0.31	0.09	0.17	0.26	-0.07	-0.18	-0.11	-0.21	-0.19	-0.13	0.07	-0.13	-0.01	0.56	-0.38	0.09	**1**

Model training and evaluation

We used input samples as a comma-separated value file of *H. suaveolens* for 100 occurrence points to construct models using Maxent 3.4.1 (Phillips et al. 2020). Different studies have been accomplished using various modeling tools, but MaxEnt has been found to perform best and consistently (Elith et al. 2006). To determine the most significant variable contributor in model fitting, we enabled Jackcknife test with logistic output format. In order to evaluate model accuracy, enable the area under curve (AUC) option based on test data. To ascertain the best result, the parameter was set at 10 for multiple model runs and 20 percent was set for the model test.

Delineation of risk zone area

MaxEnt output describes the probability of occurrence of species based on area under curve (AUC) value, ranging between 0-1. The areas < 0.5 (AUC value) are assigned as non-suitable and > 0.5 refers to suitable for the occurrence of species. We assumed two category classes of invasion risk based on AUC value range (0-1), viz., for AUC values >0.5 as high-risk zone and < 0.5 as the low-risk zone. Further, we used the Forest Survey of India (FSI 2019) based forest type map (FTM) across different forest type classes to evaluate the invasion distribution response across different forest type classes.

Model performance

The calculated average test AUC value for 2020 was 0.820 with standard deviation 0.083 and for 2050 was 0.849, 0.852, 0.847, 0.837 with a standard deviation of 0.022, 0.072, 0.028, 0.081 under RCPs 2.6, 4.5, 6.0 and 8.5, respectively (Fig.2).

The Jackknife test analyzes the significance of predictor variables in model fitting (Fig.3). The analysis showed that bioclimatic variables Bio_2 (mean diurnal range (mean of monthly (max temp-min temp)) contributed most in limiting the distribution of *H. suaveolens* for the year 2020 and for 2050, Bio_1 (annual mean temperature) contributed the most across all the RCPs.

The species response to the most contributing variable is demonstrated through Fig. 4. The results show that the annual mean temperature value ~ 10.5 ° C is the optimum value for the likely occurrence of *H. suaveolens* for the current scenario, and beyond this value the probability of occurrence of species is decreasing gradually. For the future scenario, mean diurnal values in the range of ~28-30 ° C are most optimum for the occurrence of *H. suaveolens* in the tropical conditions of Jharkhand, which is consistent with its native range (Raizada 2006, Barbosa et al. 2013).

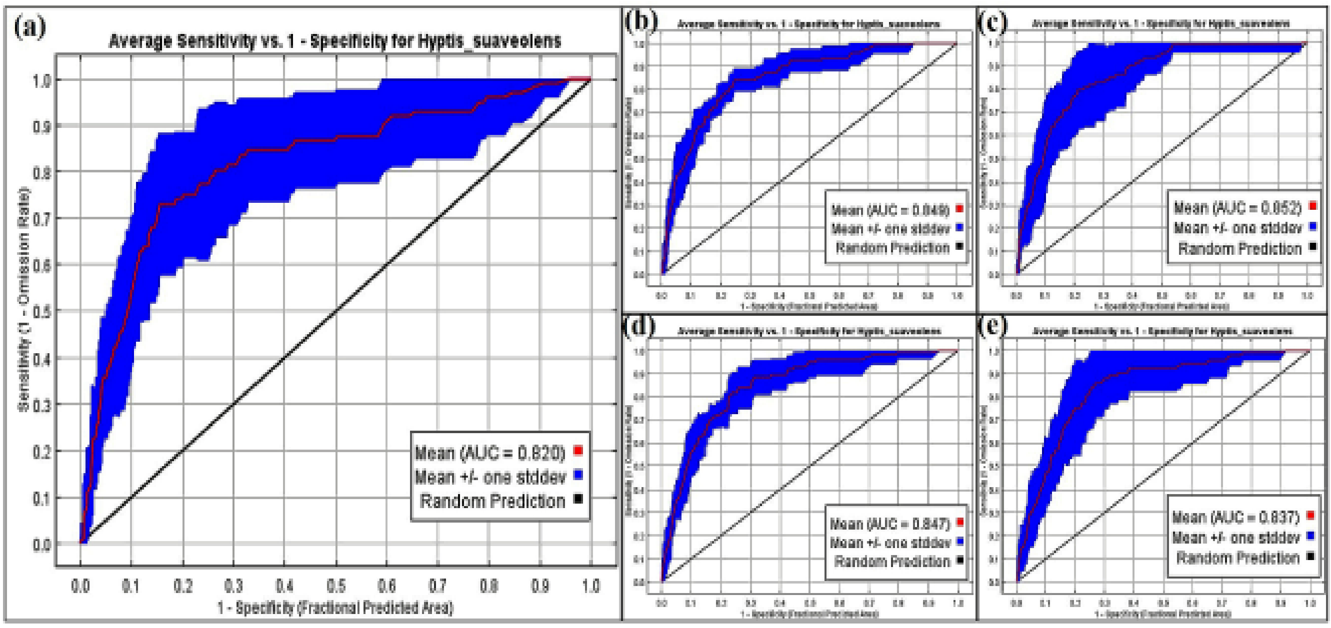

Figure 2. AUC graph for the year (a) 2020 and for the year 2050 under (b) RCP 2.6, (c) RCP 4.5, (d) RCP 6.0, (e) RCP 8.5

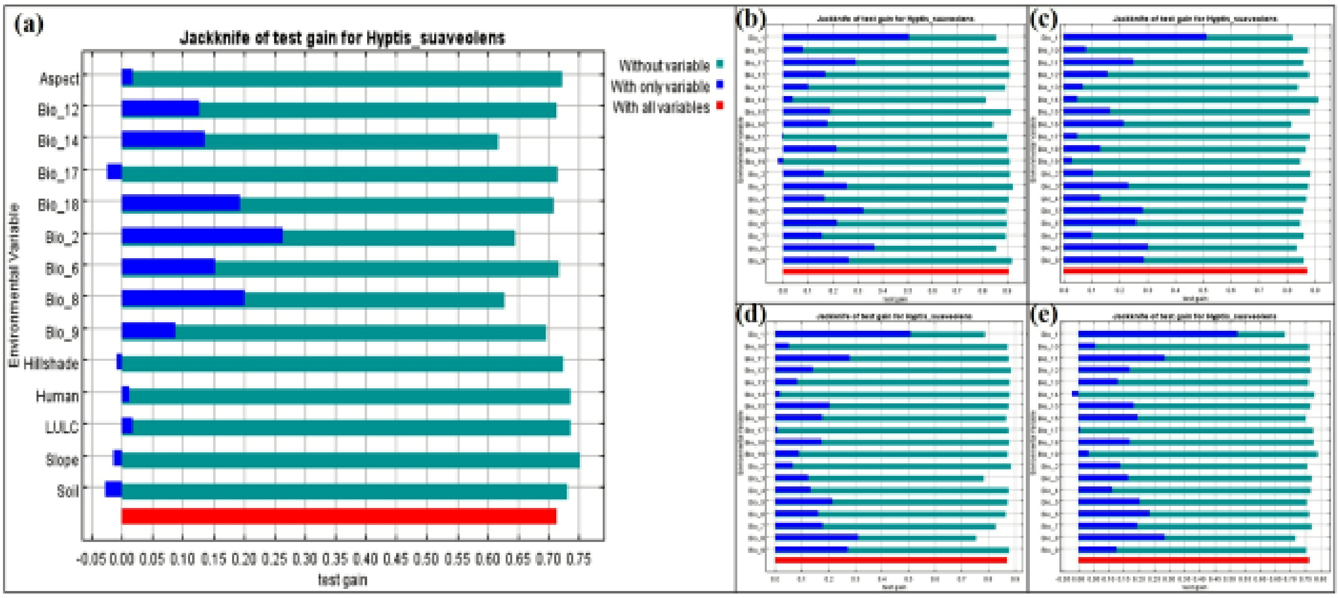

Figure 3. Jackknife test gain result on AUC for a) 2020 and for the year 2050 under (b) RCP 2.6, c) RCP 4.5, (d) RCP 6.0 (e) RCP 8.5

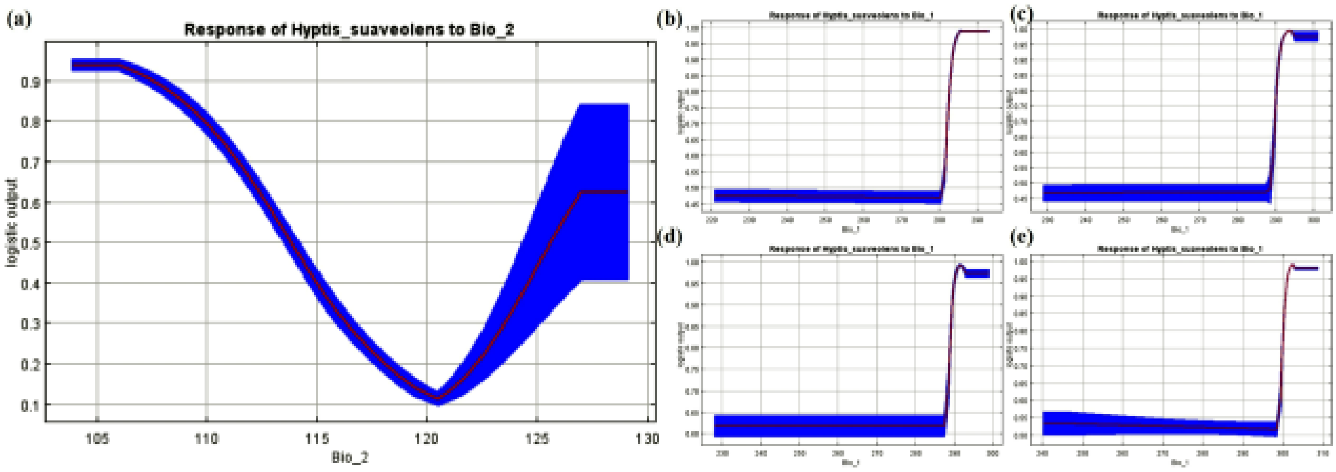

Figure 4. Species response curve for (a) 2020 and (b-e) 2050 under different RCPs i.e. 2.6, 4.5, 6.0 and 8.5. Curve (a) demonstrates optimum range of occurrence of *H. suaveolens* distribution for bioclimatic variable Bio_2 upto 10.5°C and gradually decreasing onwards. The decreasing trend reverses beyond the value ~12°C and increases for value up to ~12.7°C and beyond that it takes the form of a straight line. But the occurrence probability is negligible for this range. For the future scenario (b) shows the occurrence probability of *H. suaveolens* to that bioclimatic variable Bio_1. Chart demonstrates that values ranging ~28-30.5°C as optimum range for the occurrence of *H. suaveolens* across different RCPs.

Physical validation of model fitness

The field verification of the modeled potential distribution range of *H. suaveolens* was carried out through on-the-ground validation to 31 new sites. These location points were not part of the initial field surveys conducted for the collection of occurrence data of *H. suaveolens*. It was found that 15 sample points out of 18 visited locations occurred under the high-risk zone and 11 sample points out of 13 sites occurred under the low-risk zone. The statistical analysis for the field validation achieved an overall accuracy of 83.87% with a kappa coefficient of 0.84 (Table 2).

Table 2. Confusion matrixfor validation of potential distribution area of *Hyptis suaveolens* under different classes for the current scenario

Classes		Field Reference	
		High-Risk Zone	Low-Risk Zone
Map Reference	High-Risk Zone	15	2
	Low-Risk Zone	3	11
Total		**18**	**13**
Error of Commission		0.16	0.15
User Accuracy		0.83	0.85
Error of Omission		0.12	0.21
Producer Accuracy		0.88	0.78
Overall Accuracy		83.87	
Random Accuracy		0.006	
Kappa coefficient		0.84	

RESULTS

Projected distribution range of *H. suaveolens*

The potential distribution range of *H. suaveolens* for the years 2020 and 2050 was modeled using MaxEnt (Fig. 5). The study revealed that currently about ~9.09% (7242.15 km^2) of the total geographical area of Jharkhand is under the high-risk zone of *H. suaveolens* invasion and this may further extend up to ~9025.36 km^2, 8571.7 km^2, 8353.91 km^2, and 8646.39 km^2 for RCP 2.6, 4.5, 6.0 and 8.5, respectively. The projected expansion for 2050 in the high-risk zone of *H. suaveolens* distribution is in the range of approximately ~10.48%-11.32% of the total geographical area of Jharkhand.

Agro-climatic sub-zone wise distribution analysis

The agro-climatic sub-zone-wise analysis revealed that for the current scenario most of the potential distribution of *H. suaveolens* occurred under the sub-zones IV and VI (Fig. 6). The study showed that at present, ~4391.99 km^2 area of sub-zone IV that constitutes approximately ~5.51% of the total geographical area of Jharkhand is potentially under

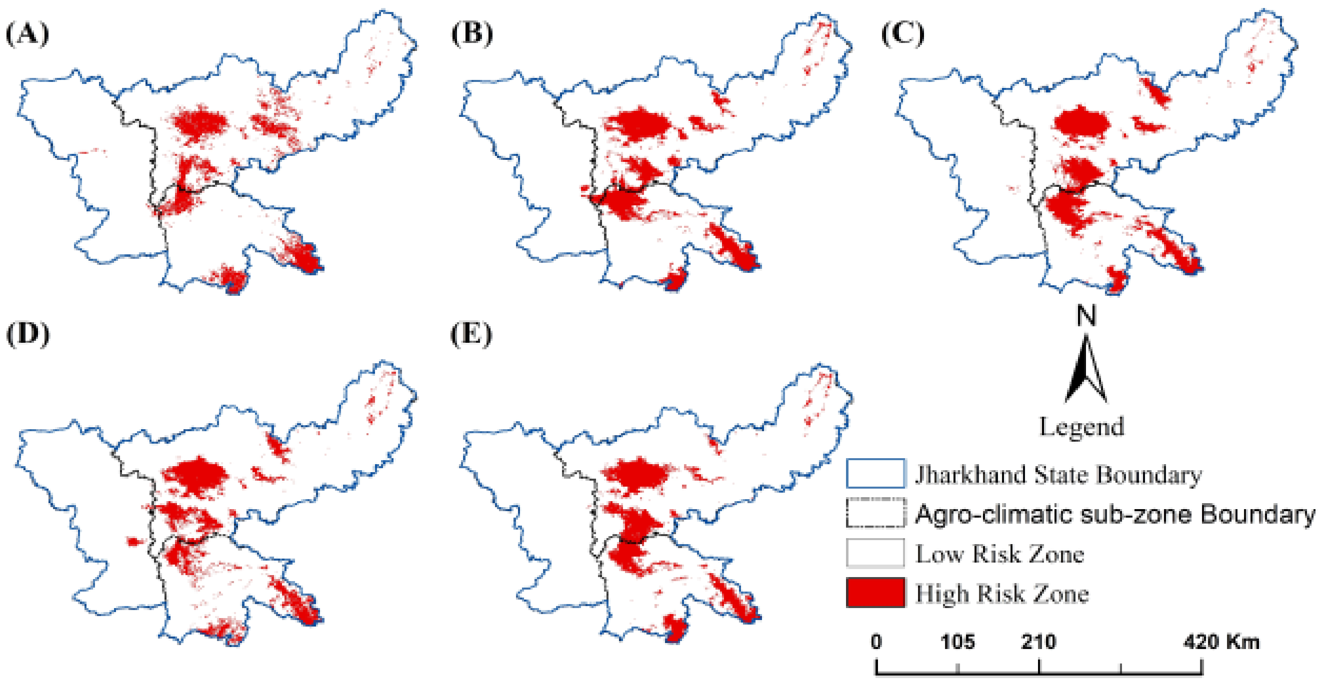

Figure 5. Projected distribution map of *H. suaveolens for* (A) 2020 and for the year 2050 (B-E) RCP 2.6, 4.5, 6.0, and 8.5.

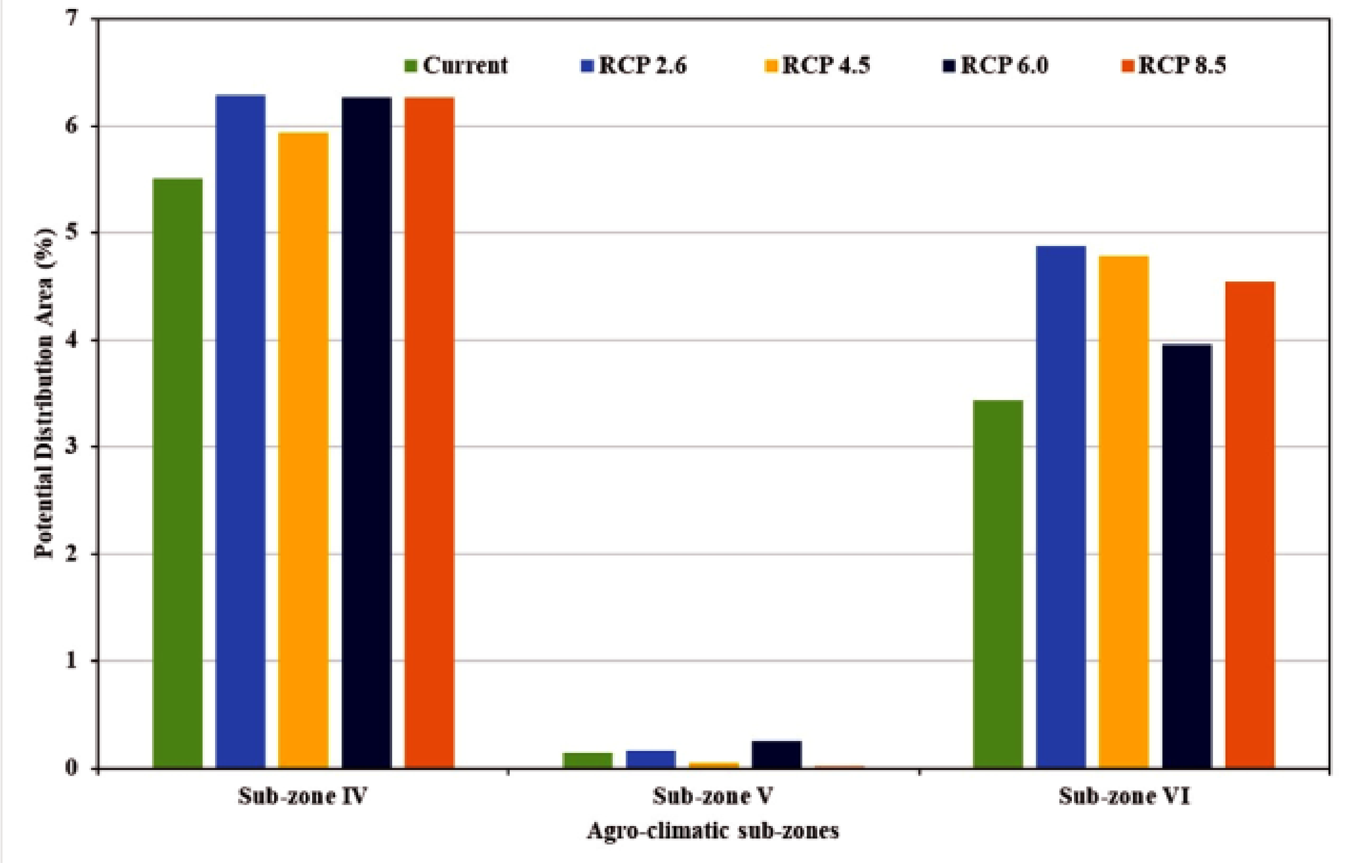

Figure 6. Agro-climatic sub-zone wise distribution of *H. suaveolens*

high risk of invasion threat of *H. suaveolens* distribution, and depending upon future RCP scenario, the invasion may extend in the range of ~5.93%-6.29% by 2050. Similarly, for the sub-zone VI ~2743.23km^2 area (3.44% of the total geographical area of Jharkhand) is under potential invasion range of *H. suaveolens* and this may further increase up to 3.95%-4.88% by 2050. In contrast, a comparatively very small area ~106.93 km^2 of sub-zone V is under the potential threat of invasion of *H. suaveolens,* and results for the future scenario showed the distribution range to remain more or less the same or even decrease to ~0.02%.

Potential distribution range of *H. suaveolens* under different Forest type category

The forest type-wise distribution analysis showed that approximately ~87.6% potential distribution of *H. suaveolens* occurred under non-forest and tropical dry deciduous forests classes and for other classes the model predicted scanty distribution (Table 3 and Fig. 7). A very negligible pattern of distribution in the range of ~0- 1.57% occurred for the rest of the forest type classes.

DISCUSSION

In the present study, the potential distribution range of *H. suaveolens* was modeled for 2020 and 2050 under different RCPs using MaxEnt. The study's outcome exhibits the wide distribution of *H. suaveolens* in the northern and central parts of the Jharkhand with scattered distribution patterns in the eastern and southern parts for the current scenario. The projections for 2050, exhibits the distribution to continue in the existing areas with further expansion in the south and eastern part of Jharkhand. Various studies conducted globally had predicted the increased threat of distribution range of *H. suaveolens* infestation in the future (Shreshtha et al. 2018, Guo et al. 2012, Peterson et al. 2008, Bronniman et al. 2007) and may have a direct impact on the phyto-sociological composition of the ecosystem (Sharma et al. 2017).

The predictor variable analysis showed that the bioclimatic variable Bio_1 (annual mean

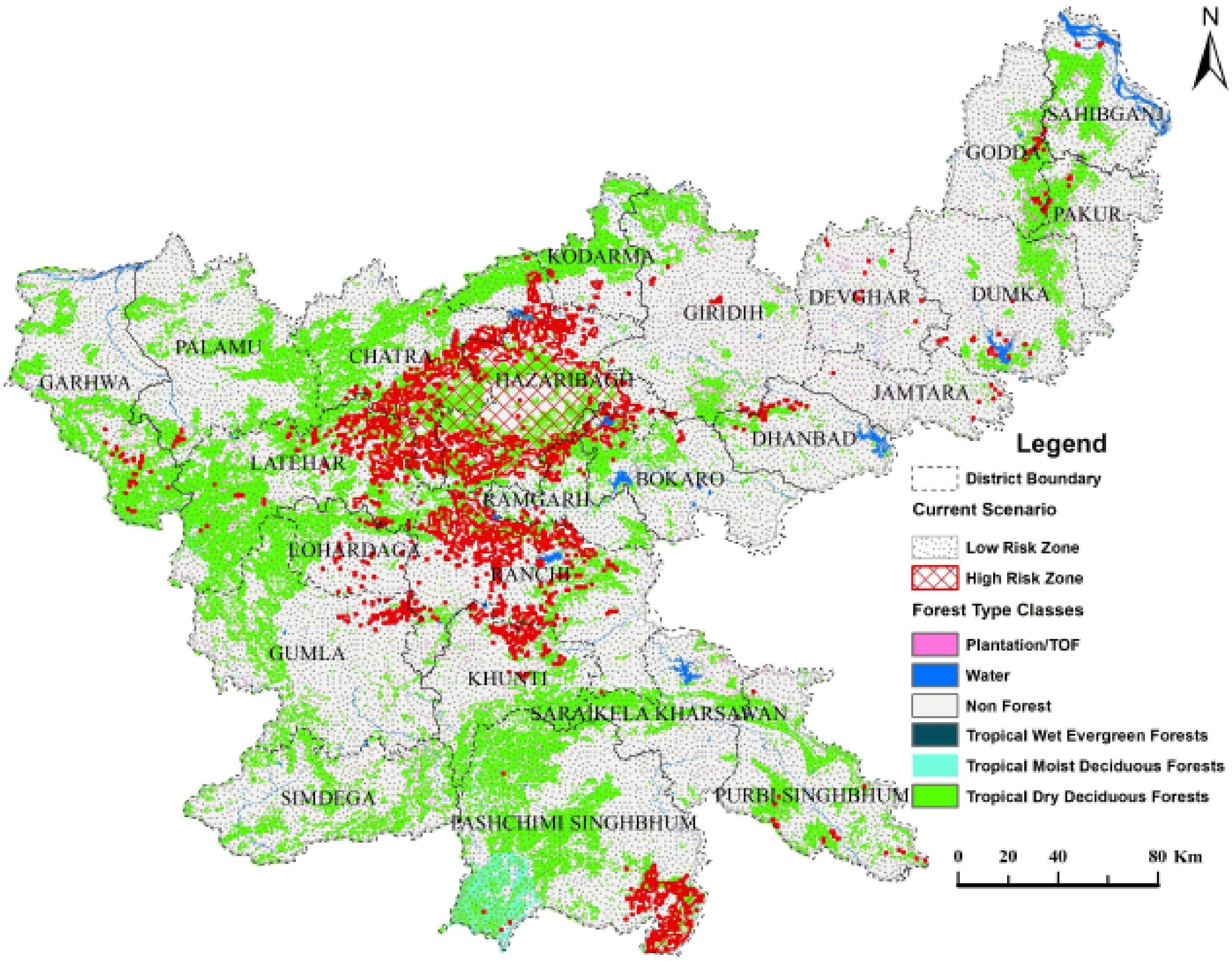

Figure 7. Projection of potential distribution range of *H. suaveolens* with respect to forest type classes.

Table 3. Forest type wise potential distribution area of *Hyptis suaveolens* under different classes for the current scenario

Forest Type Classes	Area (km^2)			Area (%)	
	High Risk	Low Risk	Total	High	Low
Tropical Wet Evergreen Forests	0	0.42	**0.42**	0	0
Tropical Moist Deciduous Forests	14.32	552.57	**566.89**	0.02	0.69
Tropical Dry Deciduous Forests	2448.04	18878.89	**21326.93**	3.07	23.68
Plantation/TOF	82.62	1251.4	**1334.02**	0.1	1.57
Waterbody	20.83	828.83	**849.66**	0.03	1.04
Non-Forest	4676.34	50959.74	**55636.08**	5.87	63.93
Total	7242.15	72471.85	**79714**	9.09	90.91

temperature) followed by Bio_8 (mean temperature of wettest quarter) most explains the potential distribution of *H. suaveolens* for the existing state of the climate and compliments that *H. suaveolens* increased with an alleviated mean temperature of the wettest quarter (Padalia et al. 2014). For 2050, the bioclimatic variable Bio_2 (mean diurnal range) contributed most in limiting the distribution of *H. suaveolens* across all RCP scenarios. The optimum range for both the most contributing predictor variables values for the occurrence of *H. suaveolens* very much matches with the values to its native occurrence range and suggests it may invade habitats with similar climatic conditions (Sharma et al. 2009). The higher probability of occurrence of *H. suaveolens* to low diurnal range suggests that *H. suaveolens* prefer humid conditions and maximum presence of *H. suaveolens* distribution occurred between 450 m to 700 m altitude range and reduced beyond 1000 m (David et al. 2021). The heterogeneous characteristics of the landscape, such as elevation, slope, aspect, landscape metrics, soil properties, land disturbances, ecosystem properties, etc., are the major influencing factors of the invasion of *H. Suaveolens* in the western Himalaya (Kumar et al. 2019).

The agro-climatic sub-zone-wise analysis exhibited the dominance of *H. suaveolens* in sub-zone IV for the current scenario (Divakara et al. 2013, Padalia et al. 2015). The future projections for 2050 exhibited the dominance pattern of invasion to continue in sub-zone IV followed by sub-zone VI. In contrast, depending upon RCPs, the study predicted a decline in potential invasion area for sub-zone V, by 2050 with maximum contraction under RCP 8.5. This indicates with a projected increase in radiative forces from RCP 4.5 to RCP 8.5. The climatically suitable areas conducive to the spread of *H. suaveolens* under sub-zone V might decrease (Poudel et al. 2020). A note of caution is due here as the generalization of these results is subject to certain limitations and might apply differently to different species.

The occurrence analysis of the potential distribution range of *H. suaveolens* to different forest types of Jharkhand showed the majority of the potential high-risk invasion areas in tropical dry deciduous forests and non-forest classes. Field surveys confirmed the distribution of *H. suaveolens* along open and disturbed forest patches, and around forest fringe. These findings are in accord with the earlier findings that reported that *H. suaveolens* prefers dry, open spaces and invades rocky landscapes of dry deciduous forests (Mudgal et al. 1997, Stone 1970). The future distribution probabilities of *H. suaveolens* are high in the fringe of the native natural forests (Padalia et al. 2015).

The present research provides insight into the potential distribution range of *H. suaveolens* in Jharkhand. The findings of the study enhanced our understanding of the distribution ecology of *H. suaveolens* (Fig. 8). One of the strengths of the present study was the on-the-ground validation of projected potential sites of *H. suaveolens*. However, some limitations need to be mentioned regarding the methodology of the present study. The species distribution modeling approach uses bioclimatic variables to assess the likelihood of occurrence of any species in a region or space. But the bioclimatic variables due to the coarser resolution may lead to uncertainty in the estimated area, mainly when dealing with regional issues. Thus results need to be interpreted with caution and further understanding of the environmental conditions and species interaction at a local scale is crucial in reaching any conclusion.

CONCLUSION

The present study aimed to model the potential distribution range of *H. suaveolens* under the current and future climatic scenarios for Jharkhand. The study demonstrated the wide distribution of *H. suaveolens* across Jharkhand with prominent distribution in the northern and central parts of the region. The findings of the study showed dominance of distribution in sub-zone IV and VI. This distribution pattern continues with further expansion in the eastern and southern parts of the state encompassing agro-climatic sub-zones IV and VI but sub-zone V where study indicated a decreasing trend of invasion in the future. Another finding of the study indicates tropical dry deciduous forest and open and non-forest areas are at greater risk of the invasion of *H. suaveolens*. The study's outcome should prove particularly valuable to the forest managers in identifying and prioritizing areas for the interventions. The weed management component should be given high priority and mandatorily included in the forest management plan, and particularly important for the management of protected areas.

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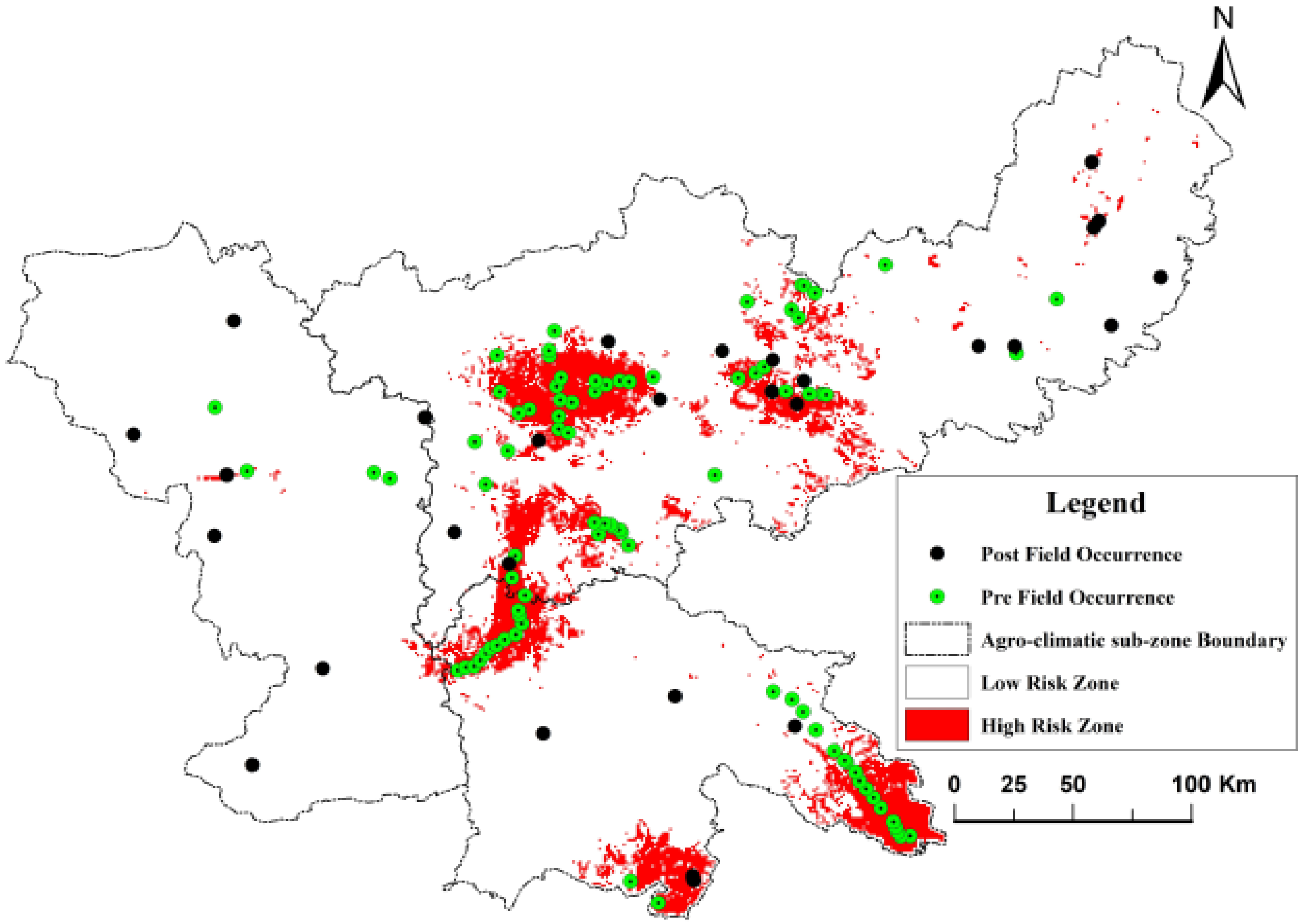

Figure 8. Potential distribution map of *H. suaveolens* with projection of occurrence data points recorded during initial field surveys and physical verification of projected site

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