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Predicting suitable habitat of an invasive weed *Parthenium hysterophorus* under future climate scenarios in Chitwan Annapurna Landscape, Nepal

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Abstract: Chitwan-Annapurna Landscape (CHAL) in central Nepal is known for its rich biodiversity and the landscape is expected to provide corridors for species range shift in response to climate change. Environmental assessments have identified biological invasions and other anthropogenic activities as major threats to the biodiversity in the CHAL. One of the rapidly spreading Invasive Alien Plant species (IAPs) in the CHAL is *Parthenium hysterophorus* L., a neo-tropical invasive weed of global significance. This study aimed to investigate the current and future projected suitable habitat of *P. hysterophorus* in the CHAL using MaxEnt modelling in three "Representative Concentration Pathways" (RCPs 2.6, 4.5 and 8.5) corresponding to different greenhouse gases emission trajectories for the year 2050 and 2070. A total of 288 species occurrence points, six bioclimatic variables - mean diurnal range, isothermality, annual precipitation, precipitation of driest month, precipitation seasonality, precipitation of driest quarter and two topographic variables (aspect and slope) were selected for MaxEnt modelling. Potential range shift in terms of increase or decline in the suitable habitat areas under the projected scenarios were calculated. Slope and annual precipitation were the most important variables that explained the current distribution of *P. hysterophorus*. Twenty percent of the total area of CHAL was predicted to be suitable habitat for the growth of *P. hysterophorus* in the current climatic condition. Highest gain in the suitable habitat of this noxious weed was found under RCP 4.5 scenario in 2050 and 2070, whereas there will be a loss in the

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suitable habitat under RCP 8.5 scenario in 2050 and 2070. Out of four physiographic regions present in CHAL, three regions - Siwalik, Middle Mountain and High Mountain have suitable habitat for *P. hysterophorus* under current climatic condition. The mountainous region is likely to be affected more than the Siwalik region by further spread of *P. hysterophorus* in the future under low (RCP 2.6) to medium (RCP 4.5) emission scenarios. The suitable habitat for this weed is likely to increase in the protected areas of mountain regions (Langtang National Park, Annapurna Conservation Area and Manaslu Conservation Area) in the future. The results have revealed a risk of spreading *P. hysterophorus* from present localities to non-invaded areas in the current and future climatic condition. Such risk needs to be considered by decision makers and resource managers while planning for effective management of this weed to reduce its ecological and economic impacts in the CHAL.

Keywords: Parthenium weed; Ecological Niche Model; MaxEnt; Invasive species; Habitat suitability

Introduction

Biological invasions are considered vital components of global change causing impact on native biodiversity, agriculture, ecosystem processes and ecosystem services (Vitousek et al. 1997; Ricciardi et al. 1998; Pejchar and Mooney 2009; Paini et al. 2016). Climate change and biological invasions have gained much interest because of their emergence as major threats to biodiversity, habitat loss and species extinction (Vitousek et al. 1997; Dukes and Mooney 1999; Thomas et al. 2004). The adverse effect of invasive species is further exacerbated by ongoing climate change (Simberloff 2000). Some elements of global change such as the increased concentration of carbon dioxide and change in land use patterns are likely to have synergistic roles in the spread of invasive species (Dukes and Mooney 1999; IPCC 2014). Rapid growth rate, a typical characteristic of Invasive Alien Plant species (IAPs), supports their quick response to the changing climate and allows invaders to expand into new ranges (Thuiller et al. 2007; Bradley et al. 2010). Increased temperature and CO_2 due to climate change enhance the performance of IAPs more strongly than native plant species (Liu et al. 2016). Altered introduction and dispersal mechanisms, shifting of the geographical range of invasive species, establishment of new invasive species, altered impact and distribution of existing invasive species, and change in effectiveness of control strategies are the main consequences of climate change for invasive species, and continue to increase the extinction risk of many terrestrial species (Sutherst et al. 2000; Hellmann et al. 2008; IPCC 2014).

Ecological niche models are increasingly being used to develop predictions concerning current and future suitable habitat of species based on the species' current occurrence, which can be useful for many aspects of resource management and conservation planning including invasive species risk assessment (Guisan and Thuiller 2005; Franklin 2009). The possibility of species invasion before their introduction to new areas can also be predicted with the help of modelling procedures (Peterson and Vieglais 2001).

A large number of general and specific software packages and systems of ecological niche modelling techniques are being used to predict suitable habitat of species (Franklin 2009). Among them, maximum entropy (MaxEnt) is a general-purpose machine learning technique that can be applied to presence-background data to generate habitat suitability predictions using environmental variables (Phillips et al. 2006). It is widely used in modelling the potential suitable habitat of invasive species as it has shown higher predictive accuracy using presence only data (Franklin 2009). Absence data for invasive species may not be reliable because the species may be under expansion process and might not have undergone equilibrium state. Such absence data may mislead the modelling procedure if the modelling is being considered to estimate the complete area at risk for invasion (Jimenez-Valverde et al. 2011).

Nepal is ranked as the third most threatened agricultural country in terms of introduction of invasion species to agriculture because of international trade of agricultural products (Paini et al. 2016). *Parthenium hysterophorus* L., a native of tropical America, has become one of the noxious weeds of agriculture in 48 countries and five continents across the world in the last 60 years (Haseler 1976; Shabbir et al. 2019). In Nepal, *P. hysterophorus* is spreading rapidly and has already invaded diverse regions ranging from southern lowland plain to mountain regions in the northern part of the country up to the elevation of ca. 1900 m asl (Shrestha 2016). It is a major problem in shrubland, grassland, rangelands, agro-eosystem and residential areas. It alters plant species composition, displace important species and soil nutrient content. It also causes health hazard to human by developing eye inflammation and skin dermatitis. Livestock develop skin lesions and produce bitter milk when *P. hysterophorus* is used as fodder (Shrestha et al. 2015).

Few studies have been conducted on the impact of climate change on the distribution and probable spread of *Parthenium hysterophorus* in broader ecological ranges including Nepal Himalaya in the future (Mainali et al. 2015; Lamsal et al. 2018; Thapa et al. 2018; Shrestha et al. 2018). Chitwan-Annapurna Landscape (hereafter 'CHAL') located in the central Nepal with north-south habitat connectivity is known for its rich biodiversity due to its unique geographic and topographic variation (WWF 2013). The climate change related impacts have been ranked as a very high threat in CHAL with greater droughts and higher rainfall which could become significant threats for spread of diseases and pests in CHAL (MoFSC 2015). The climate change projections showed that most of the lower and mid-hill forests of CHAL are vulnerable to climate change causing extensive conversion into new vegetation types (Thapa et al. 2015). The numbers of IAPs have already been recorded in the landscape and are threatening native biodiversity (WWF 2013). Therefore, the aim of the present study is to identify and develop habitat suitability maps of *P. hysterophorus* under current and projected future climate scenarios in the CHAL. It will also help to identify the areas susceptible to invasion by *P. hysterophorus* in light of changing climate in three Representative Concentration Pathways (RCPs 2.6, 4.5 and 8.5). The result might be helpful to decision makers and resources managers while planning for effective management of this weed to reduce its spread in the CHAL and to minimize its ecological and economic impacts.

1 Method

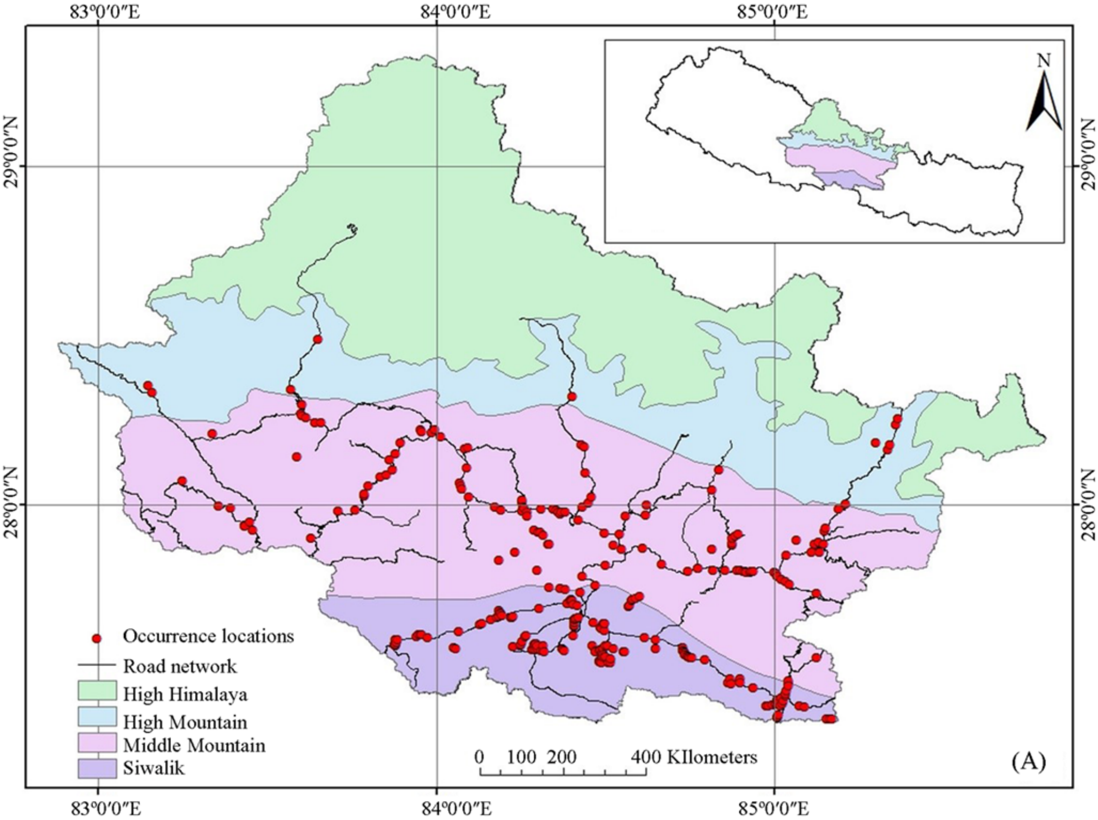
1.1 Study area

CHAL lies in central Nepal and covers 32,090 km² area including 19 districts. Out of five physiographic zones of Nepal, it represents four physiographic regions – Siwalik (200-1500 m asl), Middle Mountain (1000-2500 m asl), High Mountain (2200-4000 m asl) and High Himalaya (>4000 m asl) (DHM 2017). It has a large elevational gradient from 200 m to >8000 m asl and diverse climatic conditions including tropical, subtropical, temperate, subalpine, and alpine climate. It also comprises three National Parks – Chitwan (also a World Natural Heritage site), Parsa, and Langtang, and two conservation areas – Annapurna and Manaslu (Figure 1B). Due to its unique geographic and topographic variations, it possesses rich biodiversity. Chitwan National Park and Annapurna Conservation Area are iconic protected areas that are globally renowned for their biodiversity. The forested watersheds present in CHAL are important to sustain natural ecological communities, livelihood and economy but the continued fragmentation of subtropical and temperate forests of CHAL can result in decline of species populations and degradation of ecological services (Thapa et al. 2015). The number of naturalized plants is found higher in central Nepal (where the CHAL is located) than in eastern and western parts of Nepal (Bhattarai et al. 2014). Out of 20 IAPs reported in CHAL, *P. hysterophorus* is prioritized as the second and fourth most important invasive weed in the agroecosystem and natural ecosystem respectively by local people in the lowland of CHAL (Shrestha et al. 2019). It is expanding rapidly in urban, peri urban, and now towards the natural habitats including protected areas of CHAL with negative impacts on forage supply, and human and animal health (Shrestha 2012; Shrestha et al. 2015). The increase in temperature due to changing climate leads to encroachment of IAPs, which will ultimately affect the biodiversity of CHAL (WWF 2013).

1.2 Preparation of datasets

1.2.1 Species occurrence data

A total of 318 occurrence points of *P. hysterophorus* in the CHAL were obtained from the previous studies (Shrestha 2014; Shrestha et al. 2016; Siwakoti et al. 2016) and additional 90 occurrence points were collected by one of the



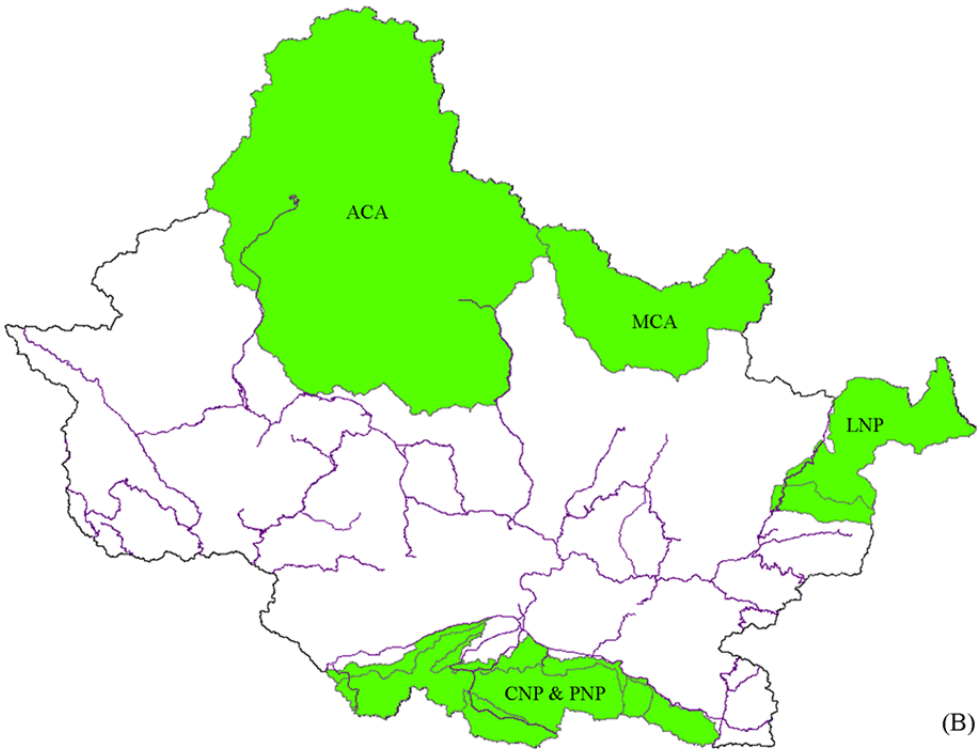


Figure 1 Study area showing (A) Physiographic regions of CHAL with occurrence points (B) Major protected areas in CHAL with buffer zone and their linkage to road network (ACA - Annapurna Conservation Area, MCA - Manaslu Conservation Area, CNP - Chitwan National Park, PNP - Parsa National Park, LNP - Langtang National Park).

(SM) in 2016 - 2018. Occurrence points were mainly collected through surveys along road networks and in residential and urban areas. Therefore, the occurrence points could potentially be biased due to easily accessible or near roadside records, which may influence the model performance by causing spatial autocorrelation (Boria et al. 2014). To remove the spatial autocorrelation and sampling bias, spatial thinning was done in ArcGIS by retaining single occurrence point randomly within 1×1 km^2 grid cells to match the spatial resolution of environmental variables (Elith et al. 2010). Spatial autocorrelation test performed in ArcGIS using Global Moran's I tool expressed the pattern of the occurrence points as the random (z-score=1.03 and p-value=0.30) (Appendix 1). The spatial thinning process resulted in 288 out of 408 collected presence records which were used to predict suitable habitat of *P. hysterophorus* under current and projected future climate (Figure 1A).

1.2.2 Variables selection

Nineteen grid based bioclimatic variables of current climatic conditions (~1960-1990) with spatial resolution of 30 arc sec. (~1km^2) (Appendix 2) were downloaded from worldclim datasets (http://www.worldclim.org/version1) (Hijmans et al. 2005). Elevation plays an important role in determining the species distribution at topo-scale in a country like Nepal where there is diverse topographic variation (Mackey and Lindenmayer 2001). Hence, Digital Elevation Model (DEM) was obtained from Shuttle Radar Topographic Mission (SRTM). Slope and aspect are important variables that cause variation in topography in determining microclimatic conditions (Bennie et al. 2008). So, these two variables were derived from DEM using ARCGIS. To reduce multicollinearity effect among the bioclimatic variables (Merow et al. 2013), a correlation matrix was built in ArcMap 10.3 using band collection statistics tool within pairs of variables and highly correlated variables having r^2 ≥ 0.8 value as cut-off threshold were removed (Appendix 3). Hence, six bioclimatic variables - (two temperature variables - Bio2 (Mean Diurnal Range), Bio3 (Isothermality), Bio12 (Annual precipitation); four precipitation variables - Bio14 (Precipitation of Driest Month), Bio15 (Precipitation Seasonality), Bio17 (Precipitation of Driest Quarter)) and two topographic variables (aspect and slope) were selected for MaxEnt modelling after multicollinearity test (Appendix 3). The main aim of the current study was to examine the effect of bioclimatic and nonchanging variables (altitude, aspect and slope) on the future probable suitable habitat of *P. hysterophorus*. The other anthropogenic variables like road network, landuse, and human population density that might have influences in the current distribution of this weed were excluded in this study due to the unavailability of the projected data for these variables in future.

A global circulation model, Community Climate System Model (CCSM4) adopted by Intergovernmental Panel on Climate Change (IPCC) - AR5, was selected based on an average annual change in means and ranks for Gangetic plain (Lutz et al. 2016) for the projections and to predict the suitable habitat of the species under different projected future climate scenarios. We have chosen three future Greenhouse Gas (GHG) emission scenarios, Representative Concentration Pathways (RCP 2.6, RCP 4.5 and RCP 8.5) for two different time periods (2050 and 2070). RCP 2.6 represents strict mitigating GHG pathway in which there will be a very low increase in radiative forcing and the projected change in global mean temperature is 1°C; RCP 4.5 represents the intermediate Greenhouse Gas (GHG) emission pathway in which there will be steady increase in radiative forcing and projected change in global mean surface temperature is 1.4-1.8°C; and RCP 8.5 represents the continuous GHG emission pathway in which there will be a highest increase in radiative forcing and projected change in global mean surface temperature is 2°C-3.7°C (IPCC 2014). Even though RCP 2.6 is now considered unfeasible (Sanford et al. 2014), it is used in the present study as a control scenario assuming that it will provide information on how more efficient measures against global warming could have influenced to predict the future suitable habitat of *P. hysterophorus*. We downloaded all above data from worldclim datasets.

Raster layers for CHAL were extracted from all the above downloaded present and future scenarios in ArcGIS. Similarly, raster layers for CHAL were prepared for slope and aspect too. All the datasets were converted into ascii raster files with a cell size of 30 arc sec. (~1km²) in ArcGIS.

1.3 Modelling

We used an open source software Maximum Entropy (MaxEnt, version 3.4.1) to predict the current and future suitable habitat of *Parthenium hysterophorus*. Logistic output was used to improve model calibration (Phillips and Dudik 2008). The random test percentage was set to 25, which means 75% of the occurrence points were used for training the model and the remaining 25% were used for testing the model. One of the advantages of MaxEnt modelling is that it does not require absence data; instead, it uses background environmental data for the entire study area by setting maximum number of background points to 10,000 (Merow et al. 2013). The number of replicates was set to 15 and the averaged model was built across all the replicates to generate the result. The model was run in subsample replicate type with 5,000 maximum iterations and 10 percentile training presence threshold rule and background predictions was selected to calculate various evaluation statistics. The remaining parameters were run with default settings (regularization multiplier – 1, convergence threshold – 0.00001). The remaining parameters were run with default settings. The resulting maps, showing the predicted probability of species presence for each raster cell of the study area for present and all future climate change scenarios, were converted into binary 'presence–absence' maps in ArcGIS through "Reclassify" tool, using 10 percentile training presence threshold value to define suitable and unsuitable areas for species, It was considered as a liberal prediction of species presence and tolerance to the environmental variables by incorporating a larger predicted area and it provides ecologically more significant results for invasive species (Liu et al. 2005; Pearson et al. 2007; Qin et al. 2014).

The suitable maps for current and all future climate scenarios were extracted. The range shift in terms of gain, loss, and stable area for all future climate scenarios compared to current suitable area were extracted from suitable map. Shifts in uppermost elevation limit of *P. hysterophorus* with future climate change scenarios compared to current was obtained by extracting the elevation data from DEM raster for all maps. Similarly, the change in area in different physiographic regions of CHAL - the Siwalik Hills, the Middle Mountains, the High Mountains and the High Himalayas and major protected areas (Chitwan, Parsa and Langtang National Parks, Annapurna and Manaslu Conservation Area) with respect to current scenarios, were calculated in all future climate scenarios.

1.3.1 Model evaluation

The performance of all models was evaluated through evaluation metrices - Area under Receiver Operating Characteristics (ROC) Curve (AUC), accuracy, sensitivity, specificity, prevalence and True Skill Statistic (TSS) (Swets 1988; Fielding and Bell 1997; Allouche et al. 2006). To calculate all of the above evaluation metrices, MaxEnt output files (sample prediction and background prediction) were processed in ARCGIS to examine error matrix value for all the model outputs (Table 1).

Table 1 Error matrix for the model outputs in different scenarios

$N = a + b + c + d$			Predicted distribution	
			Presence	Absence
Actual distribution			True positive (a)	False positive (b)
	Presence	Current	226	1996
		RCP 2.6 2050	231	2055
		RCP 2.6 2070	231	2300
		RCP 4.5 2050	243	3030
		RCP 4.5 2070	239	2882
		RCP 8.5 2050	190	1342
		RCP 8.5 2070	215	1786
			False negative (c)	True negative (d)
	Absence	Current	26	8004
		RCP 2.6 2050	21	7945
		RCP 2.6 2070	21	7700
		RCP 4.5 2050	9	6970
		RCP 4.5 2070	13	7118
		RCP 8.5 2050	62	8658
		RCP 8.5 2070	37	8214

Note: *N* is total number of events to evaluate different performance matrix scores. *N*, *a*, *b*, *c* and *d* were used to calculate evaluation statistics.

2 Results

2.1 Models performance and variables' response

The output model performance evaluated by different performance matrix scores is given in

Table 2 Performance of the output model under different evaluation statistics

Evaluation statistics	Current	RCP 2.6		RCP 4.5		RCP 8.5	
		2050	2070	2050	2070	2050	2070
Prevalence (%)	2.46	2.46	2.46	2.46	2.46	2.46	2.46
Accuracy (%)	80.28	79.75	77.36	70.36	71.76	86.31	82.22
Area under ROC curve (AUC)	0.902	0.908	0.901	0.903	0.899	0.899	0.904
True Skill Statistics (TSS)	0.697	0.711	0.687	0.661	0.66	0.62	0.675

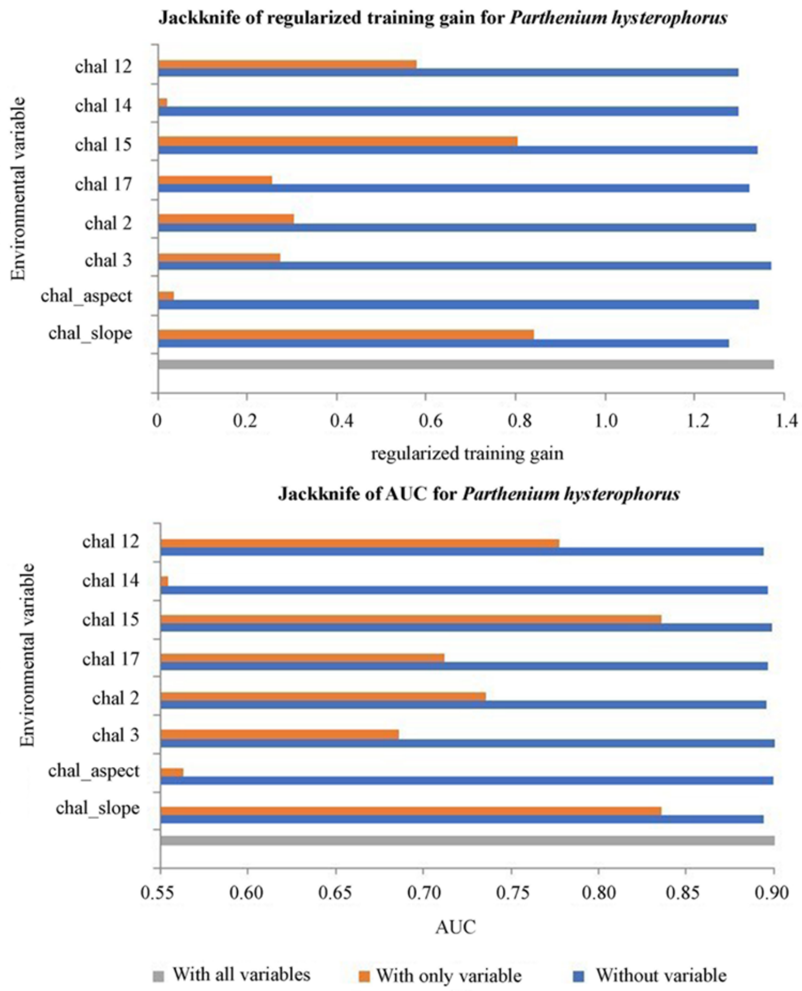


Figure 2 Jackknife test of variable's contribution in current distribution of *P. hysterophorus*. AUC means Area under Receiver Operating Characteristics (ROC) Curve.

Table 2. AUC and TSS value ranged from 0.89 to 0.9, and 0.63 to 0.69, respectively. Prevalence of all models was 2.6 and accuracy was between 71% to 87%.

Out of eight predictor variables, slope, annual precipitation (Bio 12) and mean diurnal range (Bio2) represented the top three contributing variables, with 43%, 34%, and 8% of the total contribution, respectively, to the MaxEnt model for current predicted suitable habitat (Table 3). The results of the Jackknife test of variables'

Table 3 Relative contribution of variables to the Maxent model

Variable	Percent of contribution
Slope	42.8
Bio12 (Annual Precipitation)	33.9
Bio2 (Mean Diurnal Range)	7.7
Bio15 (Precipitation Seasonality)	4.9
Bio14 (Precipitation of Driest Month)	4.1
Bio17 (Precipitation of Driest Quarter)	2.9
Aspect	1.9
Bio3 (Isothermality)	1.8

contribution (Figure 2) also showed that slope had the highest training gain and the highest AUC value compared to other variables when used independently. Similarly, the gain decreased when the 'slope' was omitted indicating that the 'slope' contained more useful information by itself. The response curve showed that the suitability of *P. hysterophorus* is high in flat areas and the suitability decreased with increase in slope of the area. Similarly, suitability increases with increase in annual precipitation (Bio12) and mean diurnal range (Bio2) (Figure 3). The slope of all occurrence points that were used for model building was below 21.5°, and 90.6% of sample points were lower than 10° (Appendix 4).

2.2 Habitat suitability in current climate and future climate change scenario

Currently, 17 out of 19 districts of CHAL had suitable habitat for *P. hysterophorus*. The habitat suitability map showed 20% of the total area of CHAL is suitable for the growth of *P. hysterophorus* in current climatic conditions (Table 4, Figure 4A). The climatically suitable habitat for the growth of *P. hysterophorus* differs in different GHG emission scenarios. The highest increase (10%) in suitable habitat has been predicted for RCP 4.5 scenario in both 2050 and 2070, but there will be decrease in suitable habitat in RCP 8.5 scenario for both years (Table 4). The effect of future climate on the predicted range of *P. hysterophorus* in CHAL was very noticeable. Area gain increases with increase in radiative forcing from 2.6 to 4.5, whereas area loss is seen in RCP 8.5 in both 2050 and 2070. Area gain is higher in the western region of CHAL than in eastern region for all future climate change scenarios (Figure 4). Some districts of western CHAL like Arghakhanchi, Gulmi, Parbat, Myagdi, Baglung, Syangja might gain suitable habitat for *P. hysterophorus* in RCP 4.5 scenario.

The present occurrence records of *P. hysterophorus* were found within elevational range between 142 and 2032 m asl (Appendix 4) but the current MaxEnt prediction showed the suitable habitat of this weed within an elevational range from 120 to 2490 m. The uppermost suitable elevation limit for *P. hysterophorus* will expand in RCP 2.6 and 4.5 but it will significantly decrease in RCP 8.5. With the changing climate, the weed may

Table 4 Percentage change in suitable area in different climatic scenario

Scenario	Suitable area (km^2)	Area covered in CHAL (%)	Change (%)
current	6374.52	19.88	
RCP 2.6 2050	6444.22	20.1	+0.22
RCP 2.6 2070	7402.80	23.08	+3.21
RCP 4.5 2050	9696.44	30.24	+10.36
RCP 4.5 2070	9299.26	29	+9.12
RCP 8.5 2050	4198.61	13.09	-6.79
RCP 8.5 2070	5564.72	17.35	-2.53

Notes: + gain, - loss; Change: Change in suitable area in CHAL compared to current prediction (%).

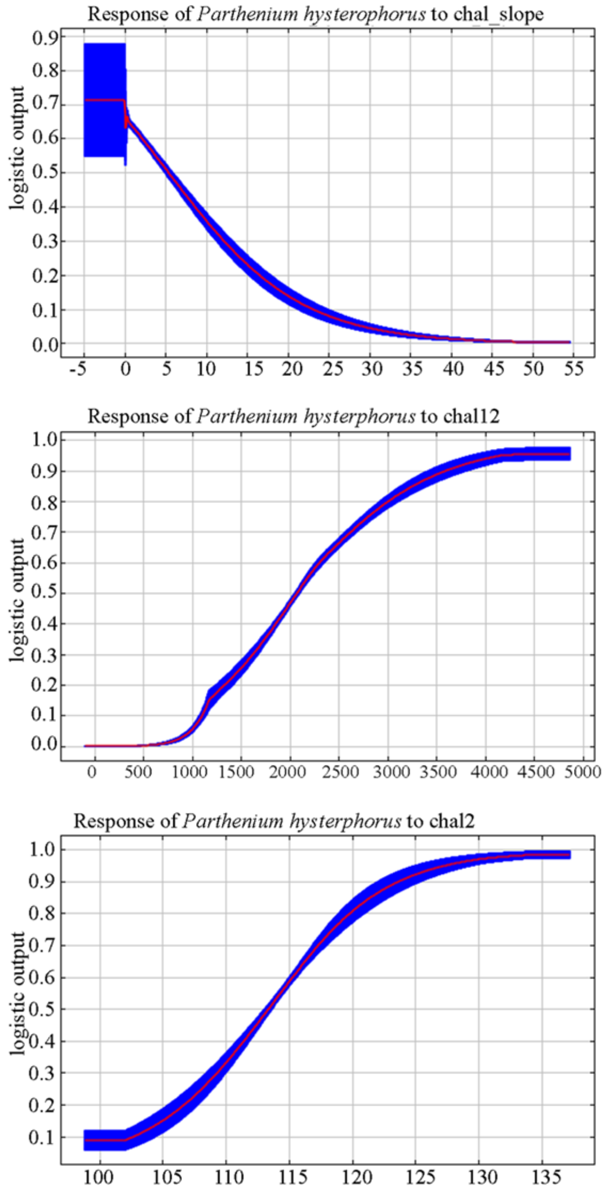


Figure 3 Response curve for probability of presence obtained for top three contributing variables slope, Bio12 (Annual precipitation) and Bio2 (Mean Diurnal Range) for *P. hysterophorus* for current condition.

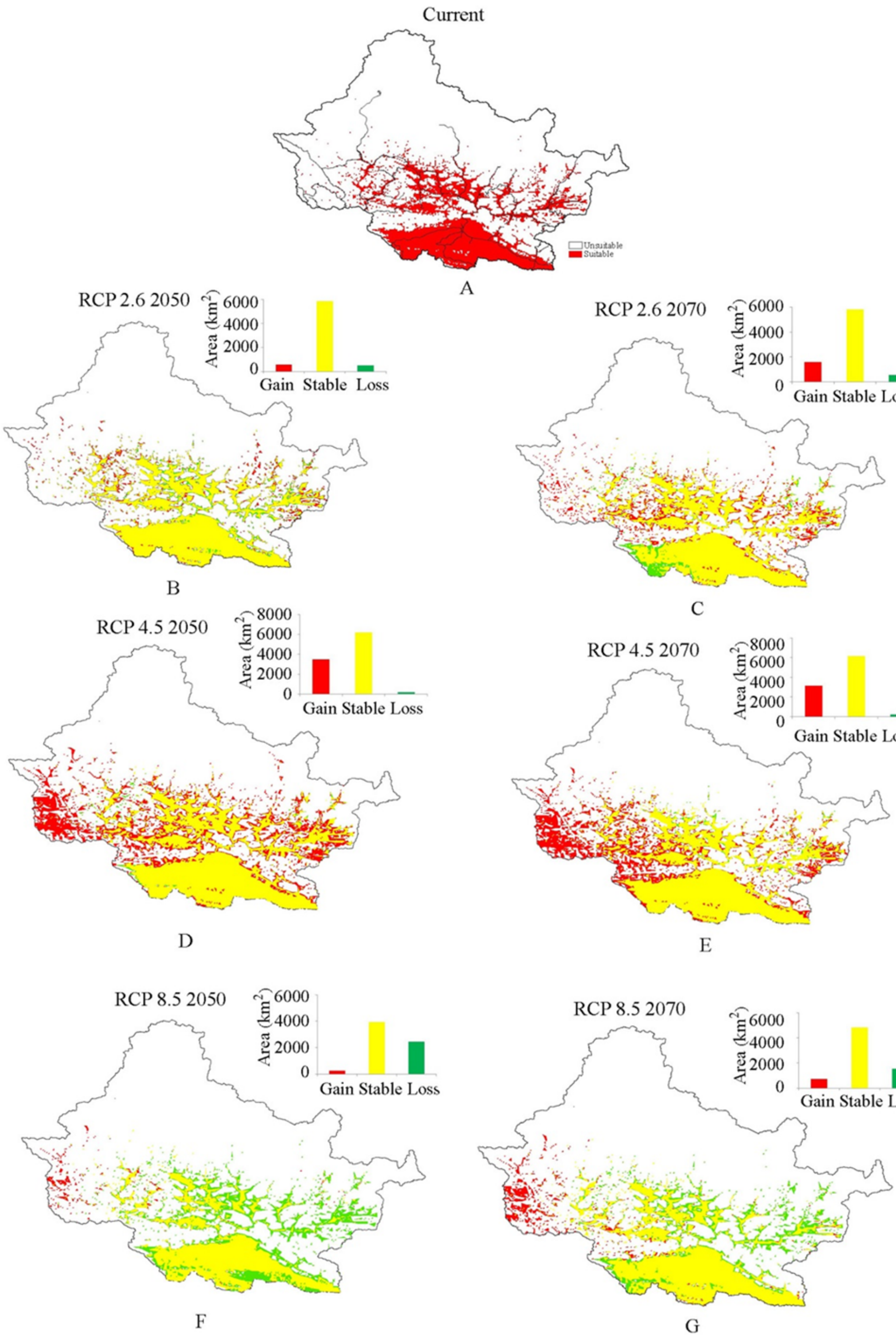


Figure 4 Current predicted suitable habitat of *P. hysterophorus* in CHAL and their linkage to road network (A), Range shifts for future climate change projected scenarios (map of the range shifts resulted from future projected scenarios – RCP 2.6, 4.5 and 8.5 for 2050 and 2070 (B - G). Area gained by *P. hysterophorus* is shown in red, stable areas are shown in yellow and areas lost are shown in green colour.

move upslope by 30 m in 2070 (RCP 2.6 and 4.5) compared to current uppermost elevation limit (Figure 5).

Out of four physiographic regions present in CHAL, three regions - Siwalik, Middle Mountain and High Mountain have suitable habitat for *P. hysterophorus* in current predicted scenario. The highest proportion of area in CHAL that is predicted to be suitable for *P hysterophorus* under current climate lies in Siwalik region followed by Middle Mountain. A similar trend is seen in all future climate change scenarios except in RCP 2.6 for the year 2070 and 4.5 for both years (Table 5). However, with the changing climate when we compared the total suitable area in each physiographic region, suitable area will decline in Siwalik region in RCP 2.6 and 8.5 scenarios for both years, but it will increase in 2050 and 2070 under RCP 4.5 scenario. There will be an increase in suitable area of *P. hysterophorus* in mountainous region in two future climate change scenarios (RCP 2.6 and 4.5). Similar decreasing trend in suitable area is predicted for the year 2050 and 2070 in RCP 8.0 scenario. Middle Mountains seem to have more suitable habitat with changing climate in the future (Figure 6). Suitable habitat for *P. hysterophorus* is predicted in all protected areas of CHAL under current climatic condition. Almost all (97%) of the total area of Chitwan and Parsa National Park is found suitable for *P. hysterophorus*. In future climate change scenario, the mountainous protected areas (Langtang National Park, Annapurna Conservation Area and Manaslu Conservation Area) will have more suitable habitat for *P. hysterophorus* particularly in RCP 2.6 and 4.5 (Table 6). Manaslu conservation area is the only protected area in CHAL of which very negligible area (0.07% of total area) have suitable habitat for *P. hysterophorus* in current climatic condition. However, the change in climate in the future might develop more suitable habitat for this weed (Table 6). Similarly, more areas in Langtang National Park will be affected.

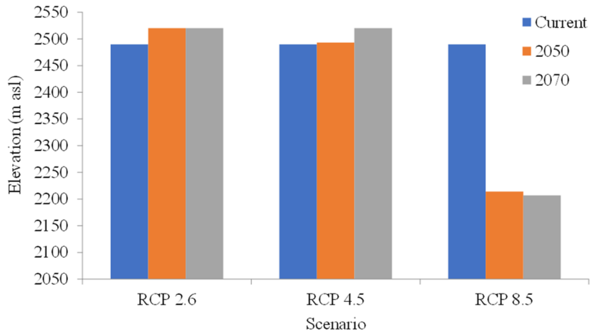


Figure 5 Shifts in uppermost elevation limit of *P. hysterophorus* with the future changing climate scenarios.

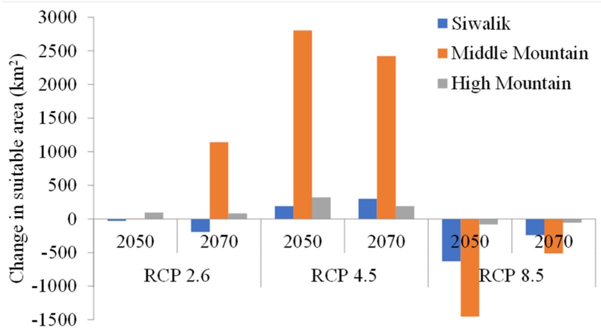


Figure 6 Change in suitable area in different physiographic regions of CHAL with changing climate in different Representative Concentration Pathways (RCP) scenarios.

3 Discussion

The model performance evaluation matrices indicated that all the habitat suitability models developed for *P. hysterophorus* performed better than random. Prevalence of all models was 2.6 % indicating 97.4% correct classification rate of the models (Fielding and Bell 1997). The model performance showing accuracy rate closer to 100%, TSS value closer to one and AUC value within the

Table 5 Total suitable area in terms of percentage in different physiographic regions of CHAL

Scenario	Total suitable area (km^2)			% Suitable area (of total suitable area in CHAL)		
	Siwalik	Middle Mountain	High Mountain	Siwalik	Middle Mountain	High Mountain
Current	3239.62	2950.86	162.98	50.82	46.29	2.56
RCP 2.6 2050	3209.46	2956.02	256.16	49.80	45.87	3.98
RCP 2.6 2070	3044.99	4091.94	246.95	41.13	55.28	3.34
RCP 4.5 2050	3430.31	5756.22	483.04	35.38	59.36	4.98
RCP 4.5 2070	3538.73	5373.75	353.74	38.05	57.79	3.80
RCP 8.5 2050	2609	1496.99	80.18	62.14	35.65	1.91
RCP 8.5 2070	2998.14	2438.66	107.68	53.88	43.82	1.93

Table 6 Change in the suitable area within protected areas of CHAL

Scenario	Suitable area for *P. hysterophorus* (km^2)			
	Langtang National Park and buffer zone (1225.56)	Annapurna Conservation Area (7754)	Manaslu Conservation Area (1645.99)	Chitwan-Parsa National Park and buffer zone (1941.29)
current	60.40	22.67	1.07	1878.03
RCP 2.6 2050	**74.13**	**27.77**	**2.95**	1874.22
RCP 2.6 2070	**69.31**	**29.72**	**6.56**	1707.59
RCP 4.5 2050	**99.49**	**55.15**	**13.35**	**1905.82**
RCP 4.5 2070	**90.58**	**31.69**	**1.55**	**1926.49**
RCP 8.5 2050	12.06	9.38	0	1524.78
RCP 8.5 2070	14.18	10.72	0	1755.41

Note: Total area of protected area is given in parenthesis. Increased areas with respect to current scenario are made bold.

range 0.8-0.9 is considered good (Swets 1988; Allouche et al. 2006). Hence, our model has shown a good performance based on the three performance matrices evaluated.

The impact of bioclimatic variables may be conditional on local topography because of the modification of local climate due to slope and aspect hence is significant for improved SDMs assessing the effect of climate change at local scale (Lassueur et al. 2006; Austin and Niel 2011). The slope of topography had the highest contribution in the predicting the suitable habitat of *P. hysterophorus* in current as well as in the future climate change scenario. This indicates that *P. hysterophorus* prefers to grow in plain land and the suitability decreases with increased slope of the land. The steeper slopes might act as buffer to some extent against the invasion probably due to higher radiation and drought events (Bennie et al. 2006). In addition, Nepal being a mountainous and agriculture dependent country where majority of people in the mountains rely on agriculture, more than 80% of land of central Nepal is under terrace cultivation by reducing the terrain slope (Neupane and Thapa 2001; Paudel and Thapa 2001). Terraced land which is no longer cropped is usually grazed and has the high probability of introduction of invasive species (Douglas et al. 1994; Lasanta et al. 2013). The seed bank record of *P. hysterophorus* (200,000 m^{-2}) in the abandoned land in India by Joshi (1991) is probably the highest record for this species. Hence, its possible spread because of abandoned terraced land in mountainous countries like Nepal should be considered while preparing management plans.

With the changing climate, the projected temperature as well as precipitation in western region of Nepal is comparatively higher (OECD 2003; NCVST 2009), leading to more favourable climatic conditions for the growth of invasive species than under current climate. Under laboratory conditions, elevated atmospheric CO_2 favours the growth of *P. hysterophorus* (Khan et al. 2014; Shabbir et al. 2014). These findings further suggest that global warming resulting from climate change is likely to facilitate invasion of *P. hysterophorus* into new areas. All of these observations stress the importance of implementation of an early detection and eradication plan of *P. hysterophorus* within the suitable areas where the weed has not yet spread widely. Adverse effects due to alien invasive species have been identified as one of the major biodiversity conservation issues in CHAL (WWF 2013). At present, *P. hysterophorus* is one of the problematic weeds in natural and agroecosystems of the Middle Mountain area in CHAL (Shrestha et al. 2019) and the situation may worsen in future due to climate change. The suitable habitat of *P. hysterophorus* will decrease by 6.79% in RCP 8.5 scenario. Lamsal et al. (2018) also found a decrease in suitable habitat by 7.44% in Himalayan range in RCP 8.5 scenario. Global mean surface temperature and annual mean precipitation will likely increase under the RCP 8.5 scenario (IPCC 2014). Hence, extreme high temperature (>40°C) and increased precipitation might be the limiting factor for the growth of *P. hysterophorus* due to compromised physiological activities and competition from other grass cover (Doley 1977; Dale 1981; Pandey et al. 2003) that may lead to the decrease in suitable habitat in extreme climate change scenarios. There is the difference in elevational range between occurrence records of *P.*

hysterophorus (142-2032 m asl) and current MaxEnt projection (119-2490m) indicating that the full extent of the distribution has probably not yet been achieved and there is also the report of this weed up to 2600 m asl in other parts of the world (McConnachie et al. 2011). Hence, there is still a chance of spread of this weed upslope in CHAL if there is not barrier for seed dispersal. The future changing climate combined with human interference may exacerbate the spread of this weed towards higher elevation.

The predicted current suitable map showed that the Siwalik region with elevation range from 200 to 1500 m asl (DHM 2017) has more suitable areas in CHAL and it is also the suitable elevational range (100-1600 m asl) for *P. hysterophorus* in its native range (Dale 1989). The scatter plot between the elevation and mean annual precipitation of the occurrence points used for modelling also showed that most of the *P. hysterophorus* presence records are confined to lower elevational range (below 700 m asl). A similar elevational range (below 500m asl) for the majority of *P. hysterophorus* has been reported from other parts of the world (McConnachie et al. 2011). *P. hysterophorus* spreads quickly along the roadsides due to vehicular movement (Bajwa et al. 2018). Invasive plants thrive along roadsides and spread quickly due to disturbance. So quick dispersal of seeds of these species with the help of vehicle over the long distances should be some of the earliest species to shift their ranges with the changing climate (Dukes and Mooney 1999). The protected areas, which are directly connected to the road network of Nepal (Chitwan National Park, Langtang National Park and Annapurna Conservation Area) are in the high risk of invasion by *P. hysterophorus*. Large area of Chitwan National Park being in the tropical (Siwalik) region have suitable habitat for *P. hysterophorus*. In the case of mountainous protected areas, Langtang National Park and Annapurna conservation area, increase in suitable habitat for *P. hysterophorus* in two RCP scenario might be further exacerbate due to their connectivity to the roads.

4 Conclusion

Our study suggests that the suitable habitat of *P. hysterophorus* in CHAL will expand by 10% in the future, causing potential threats to the native vegetation. These findings further suggest that global warming resulting from climate change is likely to facilitate invasion of this weed into new areas. All of these observations stress the importance of implementation of an early detection and eradication plan of *P. hysterophorus* within the suitable areas. Therefore, our study could be helpful to assess the risk of spread of *P. hysterophorus* from present localities to non-invaded areas in the current and future climatic conditions and would help the scientific community and policy makers in planning and effective management to reduce the ecological and economic impacts of the weed in CHAL.

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